SOUTHERN CALIFORNIA NUMBER

Volume 20 DECEMBER, 1936 Number 12

BULLETIN
of the
American Association *of* Petroleum Geologists

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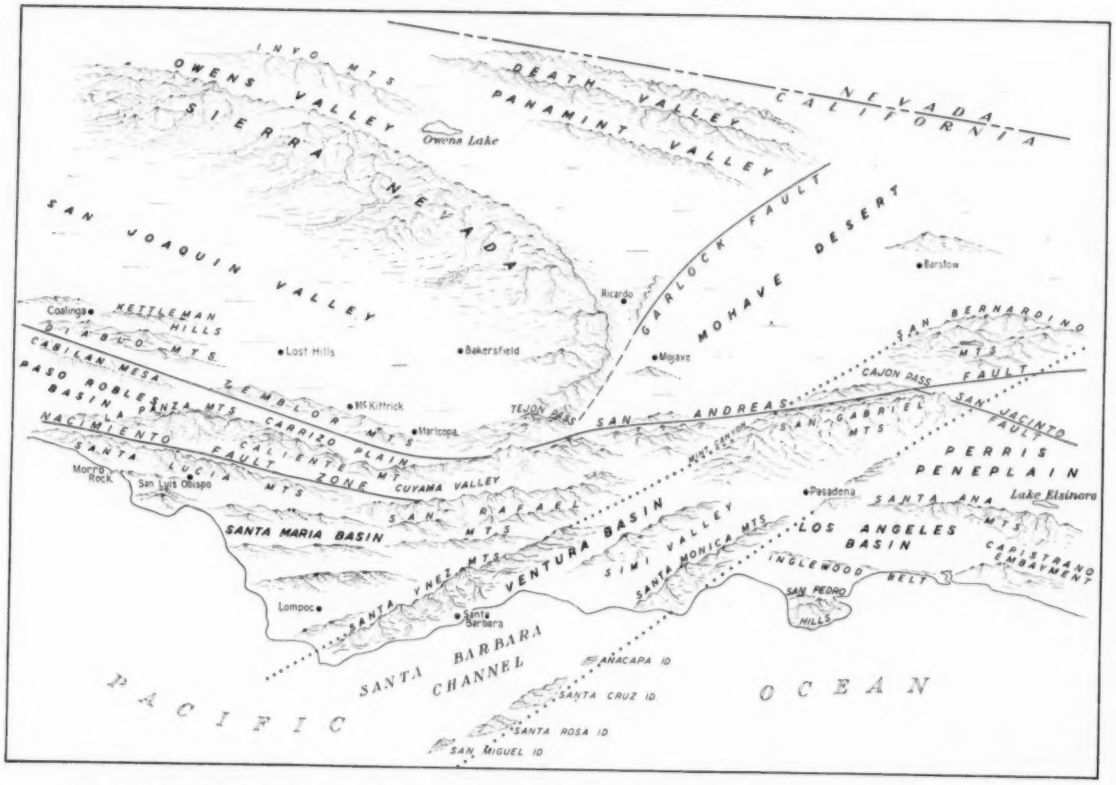

FIG. 1.—Diagrammatic relief map to show some important topographic and structural features of Southern California.

STRUCTURAL EVOLUTION
OF
SOUTHERN CALIFORNIA

3y

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PUBLISHED BY
THE AMERICAN ASSOCIATION OF
PETROLEUM GEOLOGISTS
TULSA, OKLAHOMA, U.S.A.

LONDON: THOMAS MURBY & CO., 1, FLEET LANE, E.C. 4
1936

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Published, December, 1936

COMPOSED AND PRINTED BY
GEORGE BANTA PUBLISHING COMPANY
MENASHA, WISCONSIN, U.S.A.

TO
PROFESSOR HANS STILLE,
MASTER OF COMPARATIVE TECTONICS,
THE WRITERS TAKE PLEASURE IN
DEDICATING THIS ESSAY

PREFACE

The structure of the Coast Ranges has been a subject of interest ever since the first geological expeditions came to California. A structure section from San Francisco to the Mother Lode was published as early as 1851. The geologists engaged in the surveying of routes for a Pacific Railroad about that time furnished additional structural information a little later. The first State Geological Survey, under the leadership of Dr. John B. Trask, gave some attention to the "Coast Mountains," but chiefly to their soils and mineral resources. During the sixties the Whitney survey sent men throughout the Coast Ranges and furnished a great deal of sketchy structural information.

About 1880 the State Mining Bureau was organized and the United States Geological Survey first sent men to work in California. Members of both these organizations have continued to give more or less attention to problems of Coast Range structure ever since. Their prime interest at first was in ore deposits and later in oil, but structural problems were involved in both. Shortly after 1890 H. W. Fairbanks published several structure sections along the lines of trails from one mining prospect to another in the San Rafael Mountain district. G. F. Becker gave many interesting structural data in connection with his study of the Coast Range quicksilver deposits. With the opening of the twentieth century, Eldridge, Arnold, Johnson, Anderson, and their associates and successors began mapping large areas in the Coast Ranges in connection with increasing interest in oil possibilities. Even before this time, professors of geology in the University of California and Stanford were mapping quadrangles and studying structural problems in central California, but it was a long time before such work was extended to Southern California. In 1904 Fairbanks published the San Luis Folio, the only one that has yet appeared within our limits.

Of all the different types of work, Southern California received an important share only of that devoted to oil prospects. During the first 20 years of the present century most of this work was done by members of the United States Geological Survey, who published their results in a series of valuable bulletins, many of them provided with colored geological maps. Since 1920 nearly the whole of Southern California—as the term is used in the following discussion—has been mapped in considerable detail by oil geologists and others, but publication has been sporadic and incomplete. Structural problems have been foremost in the minds of the men engaged in this work, and

many publications dealing with structural details have appeared. Many other structural problems and structural hypotheses are known and have been vigorously discussed by the men interested in them, even though nothing has been published about them.

From this historical sketch it will be obvious that any structural interpretation of Southern California must be based largely on the work of oil geologists; and that the adequacy of the data in different provinces will depend on how attractive each province has seemed to the oil-hunters. Thus Tertiary areas have in general been carefully mapped, Cretaceous areas less so, and pre-Cretaceous areas hardly at all.

In undertaking to discuss the structure of Southern California we have been limited partly by our data and still more definitely, perhaps, by our interests. We are not greatly attracted by some structural problems that seem fundamental to many geologists. The history of a structure interests us more than its mechanical cause. To call attention to this bias, we call our study "structural evolution." From the viewpoint of many of our colleagues we probably seem to be dealing only with the raw material of structural geology. We hope nevertheless that these men of different taste will be interested in our attempt to classify this raw material and present as much as possible of it in the form of maps, sections, charts, and diagrams.

This book is in a sense a sequel to *Geology of California*, which contains only brief and casual discussions of the subject of structural evolution. In order to write the present account we found it necessary to compile many geologic data, some of which did not exist at the time the earlier book was written. This new information and some new ideas that developed during the acquisition and compiling of new and old information have led to conclusions not always in harmony with those previously expressed. In such cases we have tried to avoid consistency-at-any-price, and have stated the views that seem most in harmony with the facts now known to us.

Many of our present views have been more or less strongly held by many local geologists for years. In appropriating them and stating them as our own, we would avoid claiming them as original. As a matter of fact, we do not know which, if any, of the hypotheses and opinions we now hold are original with us. All of them are to be considered ours only in the sense that we now believe them to be more probable than the alternatives that have occurred to us.

The tectonic map, in particular, is a compilation and not an original work. It includes material drawn from nearly every published

map available to us that shows geological data for any part of the area. For the areas of which no published maps exist we have drawn upon dozens of friends. At the risk of seeming partial, we wish to mention N. L. Taliaferro, H. G. Schenck, C. L. Gazin, Paul F. Kerr, W. D. Kleinpell, R. M. Kleinpell, T. Clements, A. I. Gregersen, E. R. Baddley, J. E. Eaton, and the late D. B. Seymour, all of whom have contributed important field data for larger or smaller areas. Our debt to these and many other friends and associates is very great.

In preparing the stratigraphic and other data shown in maps and charts and discussed in the text, we have likewise drawn upon all available sources of information. Some of our debts are acknowledged at appropriate places, but many others exist. Our chief excuse for not making greater effort to acknowledge specific obligations in more detail is that to do so would add very considerably to the bulk of our text. Another reason of much weight is the practical impossibility of remembering correctly how and when we obtained facts and ideas, the acquisition of which has covered several years and has involved hundreds of conversations with scores of geologists.

To our predecessors in the field of structural interpretation we wish to pay our respects in this place. Our plan of work and our desire to attain conciseness forbade making lengthy discussions of their work. We have nevertheless made use of the results of their labors, have appropriated some of them and rejected others, and been influenced even by the results we rejected, just as we expect our successors to do with our results. It would be an interesting task to write a history of structural interpretation in California, but it is not the task we set for ourselves in the present work.

Dr. Hans Ashauer drew a considerable number of our maps and diagrams; from his extensive knowledge of European geology and of the ideas of European geologists he was also of great assistance to us in our attempts to classify and interpret Coast Range phenomena. Mr. J. E. Eaton put us greatly in his debt by a critical reading of the manuscript. Mr. V. Coppard drew the geological map and many of the text figures. Many other friends and associates contributed in different ways.

Among recent writers on the problems of structural interpretation we are particularly indebted to three: Professor W. H. Bucher, author of *The Deformation of the Earth's Crust;* Professor S. von Bubnoff, author of *Grundprobleme der Geologie;* and Professor Hans Stille, author of *Grundfragen der vergleichenden Tektonik.* To the last-named geologist our debt is of so special a character that we have attempted to acknowledge it by dedicating this study to him.

For permission to make the investigation upon which our text is based, and to publish some of the scientific results, we are deeply indebted to The Texas Company, and particularly to Mr. J. A. Bermingham, vice-president and manager of the producing department for California.

R. D. REED
J. S. HOLLISTER

LOS ANGELES, CALIFORNIA
September, 1936

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CHAPTER I

INTRODUCTION

Writing informally in 1861, after spending a year in travel between the Santa Ana Mountains and the San Francisco Bay region, W. H. Brewer[1] remarked:

> The Coast Range is not a single chain, nor even parallel chains, but a system, radiating, like the spokes of a wheel, from a point near the great mass of San Bernardino.[2]

Though somewhat over-simplified, this interpretation of Coast Range structure has the merit of directing attention to a feature that gives to Southern California much of its geological interest. This is the fact that the greater number of the geological provinces into which California is divided meet here in a small area. North of the dominant Transverse Ranges lie the south ends of the Coast Ranges, San Joaquin Valley, and Sierra Nevada, and the west end of the Mohave Desert. South of the Transverse Ranges lie the so-called Continental Shelf, the Los Angeles Basin, and the northwest ends of the Peninsular Ranges and Colorado Desert.

Since the time of Brewer's pioneer studies, many different hypotheses of Coast Range structure have been more or less seriously proposed. Only with the opening of the present century, however, did the supply of facts become sufficiently plentiful to give much basis for such speculations. Beginning about 30 years ago, the United States Geological Survey has published a series of excellent areal descriptions and geological maps of scattered small areas. Most influential in moulding the views of structural theorists, perhaps, were the three Coast Range folios: San Luis, Santa Cruz, and San Francisco. By a curious accident each of these publications was devoted to a quadrangle in which two types of structural province meet. The San Luis Quadrangle, for example, includes part of the Santa Lucia Mountains in which a Franciscan basement underlies a thick series of strongly folded Upper Mesozoic and Cenozoic formations. It also includes a part of the La Panza Mountains, with granitic basement, no Franciscan, and a highly discontinuous blanket of faulted, slightly folded later rocks. The Santa Cruz and San Francisco areas are likewise crossed by the boundary between a Franciscan and a

[1] W. H. Brewer, *Up and Down California*, Yale University Press (1930), p. 236.

[2] "San Bernardino Sierra" is a name formerly applied to mountains far west of the present San Bernardino Mountains, and particularly to the San Gabriel Mountains north of Los Angeles.

"granitic" terrain. This interesting discovery seemed to support the idea that the Coast Ranges are everywhere separated into small fragments, each of which has moved up or down forever in serene disregard of its neighbors.

Concurrently with this rise of the chaotic type of structural hypothesis, additional geologic mapping has shown that the three areas covered by folios are exceptional rather than typical. The granitic parts of the San Luis, Santa Cruz, and San Francisco districts are in fact small fragments of one immense granitic province, Salinia,[3] which trends obliquely across the whole length of the Southern Coast Ranges and merges at the southeast with the Mohavian granitic province. The Franciscan areas of the three folio districts likewise extend far beyond their borders and constitute two large provinces, the Northern and Central Franciscan areas.

In spite of these discoveries, other factors have combined with the accidental location of the areas earliest mapped to strengthen the trend toward structural chaos. Faults are numerous, important, and some of them recurrently active. Facies of sedimentary rocks are so varied as to make regional correlations difficult and occasionally impossible. By their parallel difficulties in discovering regional relations, students of crustal mechanics and paleontologists have thus been driven toward the idea that regional relations do not exist. Hence the appeal of the fault-block theory to many of them. However unsatisfying such a theory may be otherwise, it serves at least to justify the difficulties of its creators.

Many parts of Southern California, particularly the mountains and deserts toward the east and south, are known even now only from reconnaissance investigations. Most of the valleys and plains and the mountains toward the north and west have been carefully and repeatedly mapped, however, and knowledge of their geology is growing rapidly. During the past ten years the foraminiferal research of oil-company stratigraphers and others has remade the stratigraphy of the marine Tertiary; vertebrate paleontologists have made great strides in tying together the history of the marine coastal basins and the nonmarine basins of the interior; detailed geologic mapping has been extended to so many areas as to furnish a comparatively adequate basis for general statements about the whole region; and deep drilling, by permitting intensive study of many thousands of samples, has revealed the third dimension of several of the larger basins to depths of two miles or more. There are at present probably few areas

[3] R. D. Reed, *Geology of California* (Amer. Assoc. Petrol. Geol., 1933), p. 12, Fig. 16, *et cetera*.

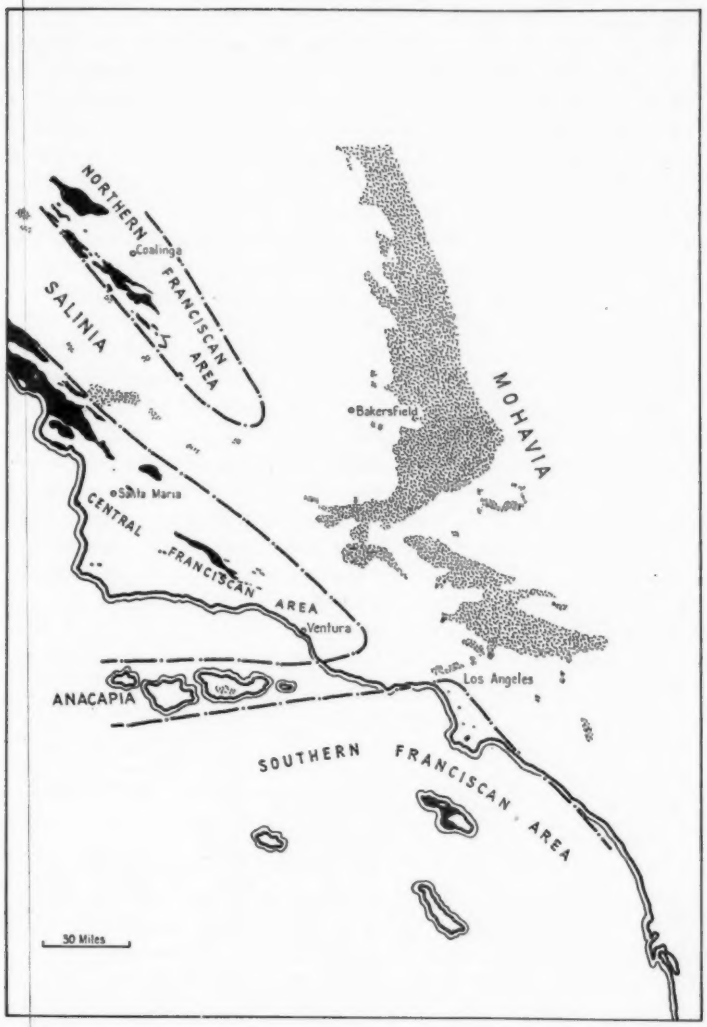

FIG. 2.—Basement map, designed to show the evidence for the classification of Southern California into six major tectonic provinces. Black areas are Franciscan outcrops; stippled areas are outcrops of granitic rocks.

of similar complexity in the world for which equally plentiful geological data are available.

In an effort to exploit these advantageous features the writers have spent more than two years in collecting and summarizing old and new data on the structure, stratigraphy, and paleogeography of this region. They have assembled all the geological maps available to them and reduced them to a uniform scale for easier comparison and study. They have collected many stratigraphic data, including especially measured surface and subsurface sections, and observations on discontinuities and discordant contacts between formations. They have also spent many weeks in the field, checking old and securing new data, especially in several centrally located but relatively inaccessible areas that were previously little known.

On the problem of fundamental structure, the writers have come to believe that post-Jurassic structural evolution has been dominated by the distribution of basement types. They have accordingly adopted or invented names for the six paleogeographic provinces into which the distribution of these types suggests that Southern California was divided during the Lower Mesozoic (Fig. 2). For the reason that, as explained in more detail later, the Franciscan deposits seem to have accumulated in basins of a kind that many geologists would consider to be typically geosynclinal, the provinces underlain by these rocks are called geosynclines. The other provinces, which seem to have been relatively positive, are given names ending in "ia," to suggest comparison with such well-known hypothetical ancient lands as Appalachia and Cascadia.

CHAPTER II

DIASTROPHIC HISTORY

From the point of view of structural history, the evolution of Southern California may be divided into three stages: a pre-Franciscan, a Franciscan, and a post-Franciscan stage (Table I). The pre-Franciscan stage, embracing all of pre-Mesozoic time, is practically unknown. The Franciscan stage included a part, and perhaps

TABLE I

STRUCTURAL HISTORY OF SOUTHERN CALIFORNIA

Major Periods	*Structural Events*	*Time Scale*
Stage of high lands	Erosion dominant	Upper Pleistocene and later
—*Coast Range Orogeny*—		Middle Pleistocene
	Recurrent transgressions, regressions, minor foldings	Lower Pleistocene Pliocene Upper Miocene Middle Miocene Lower Miocene Oligocene
Post-Franciscan (Post-Geosynclinal) Stage		Upper Eocene Middle Eocene Lower Eocene Paleocene
	—*Folding*—	
		Upper Cretaceous Lower Cretaceous Upper Jurassic Upper-Middle Jurassic Middle Jurassic to Triassic
—*Nevadian Orogeny*—		
Franciscan (Geosynclinal) Stage	Spasmodic downsinking and vulcanism	
—*Appalachian Orogeny* (?)—		Late Paleozoic
Pre-Franciscan (Pre-Geosynclinal) Stage	Conditions nearly unknown, or inferred from sketchy data	Paleozoic and Pre-Paleozoic

nearly the whole, of the Triassic and Jurassic periods. Its deposits consist of the Franciscan formation in the old geosynclines, and of some slates and phyllites of non-geosynclinal, or less distinctively geosynclinal facies in the more positive intermediate areas. Most of the non-Franciscan rocks are supposed to be Triassic and the Franciscan is commonly referred to the Jurassic, but in each case the age is determined for only a very few thin beds with generally unknown relations to the great masses of which they form part. In a structural discussion there is perhaps sufficient justification for calling all these rocks Lower Mesozoic, as is done in this book.

The post-Franciscan stage began with the deposition of the so-called Knoxville beds, which, like the better known Knoxville farther north, may be Portlandian (Upper Jurassic) at the base.[4] The stage also includes Lower and Upper Cretaceous and Cenozoic time.

Lower Mesozoic Epeirogeny

The subject of Lower Mesozoic paleogeography in coastal California bristles with difficulties. Is the Franciscan marine or nonmarine? Is it Triassic or Jurassic or both or neither? Is it a correlative of the Santa Monica phyllite and the Santa Ana Mountains Triassic? How can we treat as a unit a group of rocks consisting of varied sedimentary types, intrusive and extrusive igneous rocks, and metamorphic rocks? Would it not be nearly as sensible to treat all post-Franciscan rocks as a unit and try to give them a paleogeographic interpretation? When we think of the great number of monographs that have been written on the stratigraphy of the Triassic and Jurassic formations of other regions, and reflect that our knowledge of Franciscan stratigraphy can be summarized in a short paragraph composed mostly of doubts, we begin to realize the difficulty.

To discuss all aspects of each controversial question would take time and lead nowhere. For present purposes it will serve equally well to state briefly and categorically the present stand of the writers on the various problems. They hold that the Franciscan is dominantly marine, that it probably includes both Triassic and Jurassic deposits, that it is a correlative of the phyllites and slates of the Santa Monica and Santa Ana Mountains but represents a different facies. They defend the policy of treating the Franciscan as a unit, but only on the ground that no other treatment is possible at the present time.

That the Franciscan is a unique formation, composed of a great variety of rock types, many of which are themselves unique in California, is well known. The intrusive rocks are largely altered peridotites, the lavas are related to spilites, the siliceous rocks are radiolarian, the metamorphic rocks consist of glaucophane schist and other peculiar types. The sandstones contain many shale fragments, and have been considered nonmarine. They are highly feldspathic, like most Coast Range sandstones. As a formation, the Franciscan has still other peculiarities. The base of it, for example, has never been seen. Between it and the granitic basement only fault contacts are known. Though universally described as highly unconformable with the Knoxville, detrital fragments of any of its distinctive rocks or

[4] F. M. Anderson, "Knoxville-Shasta Succession in California," *Bull. Geol. Soc. Amer.*, Vol. 44 (1933), p. 1269.

minerals have been found in pre-Miocene rocks only in a few localities. Even now, there is no proof that the Franciscan has ever been totally removed from any locality which it once covered.

In most of these peculiarities, the Franciscan resembles those formations of other regions that are classed as belonging to the geosynclinal facies. For this reason the writers assume tentatively that the Franciscan rocks occupy areas that were in fact geosynclines (whatever a geosyncline may be)[5] during Lower Mesozoic time. The intervening areas were either non-geosynclinal or, if anyone prefers, they were geosynclinal subprovinces that lacked the peculiar features of the rest of the geosyncline.

Pre-Cretaceous Orogeny

Since only a few pre-Cretaceous rocks can be dated accurately, not much can be said about the orogenic history of this time. It is notable, however, that the metamorphic rocks associated with the granites of the "granitic basement" contain much limestone, and lack the peculiar lithologic types of the Franciscan. They resemble the basement rocks of the Mohave Desert region, some of which have yielded Paleozoic fossils. For this and other inconclusive reasons they are often considered to be Paleozoic in age. If so, and if the Franciscan includes Triassic and Jurassic, perhaps it is legitimate to guess that a late Paleozoic orogenic episode preceded the beginning of the Lower Mesozoic geosynclinal stage.[6]

That orogenic periods intervened during the geosynclinal stage itself is likely for several reasons, but unproved. It is known, for example, that detrital glaucophane is a constituent of the Franciscan sandstone. Since this metamorphic mineral is very uncommon in pre-Franciscan rocks of California, its occurrence as detritus suggests intra-Franciscan metamorphism and orogeny. If Franciscan rocks range in age from early Triassic to middle or late Jurassic, there is of course no reason why such orogenic activities should not have occurred more than once.

That an orogenic period ended Franciscan time has been generally assumed, but in the absence of satisfactory means for correlating late Franciscan and early post-Franciscan strata, uncertainty concerning the exact order of events is inescapable. Whether or not the post-

[5] For an interesting discussion of the possible nature of geosynclines as "furrows reaching to the base of the outer mantle of the sial," with labile character, distinctive sedimentation and vulcanism, *et cetera*, see S. von Bubnoff, *Grundprobleme der Geologie*, Berlin (1931), p. 176.

[6] *Cf.* Adolph Knopf, "The Mother Lode District," *U. S. Geol. Survey Prof. Paper 157* (1929), p. 9.

Franciscan pre-Knoxville orogeny synchronized with the post-Mariposa Nevadian orogeny of the Sierra Nevada, for example, is uncertain. Perhaps, as Crickmay has suggested,[7] the Nevadian orogeny consisted of several phases, each of which may have affected both Coast Ranges and Sierra Nevada, though not necessarily with the same intensity.

If the post-Franciscan orogeny was profound, as is generally assumed, it is only the more curious that no place can be cited from which Franciscan rocks have been completely removed. No locality is known, as a matter of fact, in which the base of the series can be seen. There is of course a possibility that Salinia, for example, was once covered by Franciscan rocks that were later removed by erosion. If this hypothesis is adopted, however, there seems to be no easy way to account for the well-authenticated fact that the Cretaceous strata of adjacent areas carry so little distinctive Franciscan detritus.

In the *Geology of California* this condition was tentatively explained[8] on the theory that Franciscan basins of deposition coincided with the areas in which Franciscan rocks are now found. The geosynclinal hypothesis would modify this conclusion only by suggesting that if sediments of Franciscan age did accumulate over Salinia, for example, they were not Franciscan (geosynclinal) in type, but belonged to a different facies. The supposed Triassic phyllite of the Santa Monica Mountains will serve as an example of a deposit apparently contemporaneous with the Franciscan but of different facies from it.

Post-Franciscan Mesozoic Epeirogeny

In Southern California the beds of post-Franciscan, pre-Chico age are still mapped together as the Knoxville formation. Perhaps they contain the same units as the thicker Northern California section belonging to the same time-interval, but for the present they are better discussed as a unit. They are in the main siltstone and shale with interbedded sandstone generally fine-grained and thin-bedded. The commonest fossils belong to the genus *Aucella*. Thicknesses rise to several thousands of feet.

The Knoxville sea covered much or all of the Northern and Central geosynclinal basins, but cannot be proved to have transgressed their borders (Fig. 3). It may have invaded the Southern Geosyncline also, but its deposits have not been found on any of the few mountain peaks now available for inspection.

[7] C. H. Crickmay, "Jurassic History of North America," *Proc. Amer. Phil. Soc.*, Vol. 70 (1931), p. 57.

[8] R. D. Reed, *op. cit.*, p. 78.

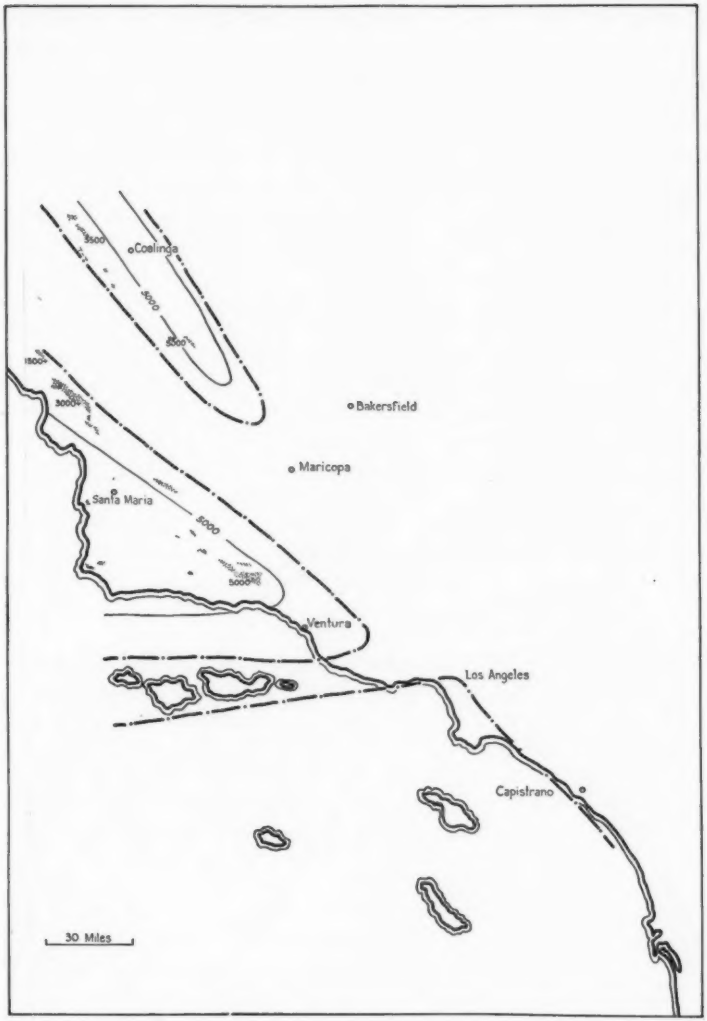

FIG. 3.—Lower Cretaceous (Knoxville) paleogeography. Province boundaries as in Figure 2. Stippled areas have Knoxville beds outcropping; figures give thicknesses in feet. Isopach lines are highly speculative.

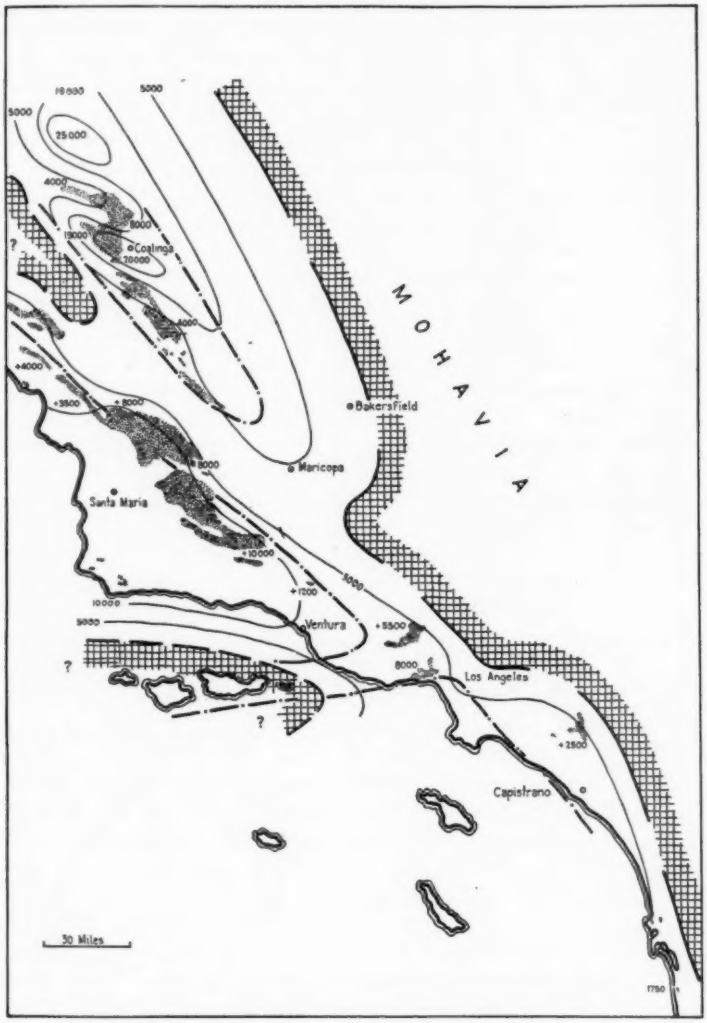

FIG. 4.—Upper Cretaceous (Chico) paleogeography, showing outcrops, thicknesses in feet, isopachs, and former land areas, of which the boundaries are doubtful, especially in case of the two western lands.

Overlying the Knoxville, in the main with unknown structural relations, is the Upper Cretaceous Chico formation (Fig. 4). It consists chiefly of shale and sandstone, but locally contains thick masses of conglomerate. In the Coalinga district and northward (central part of the Northern Franciscan Basin) a thousand feet or more of the uppermost Cretaceous consists of the Moreno shale, an organic siliceous rock resembling the Middle and Upper Miocene Monterey shale. This member, a possible correlative of the Senonian, is not known in the Central or Southern basins.

Unlike the Knoxville, the Upper Cretaceous transgressed the eastern boundary of each of the three geosynclinal basins. Chico strata are found along the eastern border of the Great Valley, though they do not crop out south of Folsom in the latitude of Sacramento; in the Simi Hills, east of the vertex of the Central Geosynclinal basin; in the central part of the Santa Monica Mountains (eastern Anacapia); and along the western slope of the Peninsular Ranges, from the Santa Ana River to San Diego. In all these areas the Upper Cretaceous is either known or reasonably inferred to lie upon non-Franciscan basement rocks (granite or slate).

The Danian is not definitely known in California but may very well be represented among some of the strata now referred either to the uppermost Cretaceous or to the Martinez.

Cretaceous Folding Episodes

The problem of intra-Cretaceous folding episodes is a difficult one. No widespread discordances have been clearly demonstrated, but there is an excellent chance that one or more may be found when the sections are more carefully studied and the distribution of the different fossil zones is adequately known. The great Chico transgression seems likely to have been accompanied or preceded by folding movements of importance, but no conclusive evidence of such movements seems to be available at present.[8a]

The conditions at the close of the Mesozoic are fortunately somewhat clearer. Even where the exact contact of Upper Cretaceous and Paleocene is in dispute, indirect evidence often strongly suggests that an orogenic episode occurred. In the Santa Ana Mountains, fortunately, the conditions are clearer than usual and, though undescribed

[8a] Since this passage was written, N. L. Taliaferro has told the writers orally of discoveries bearing on this problem that were made by him in some of the higher and more complexly folded parts of the Santa Lucia and Diablo mountains. He reports localities in which, contrary to the ordinary condition, considerable quantities of Franciscan detritus occur in Upper Cretaceous conglomerate; and also some in which basal Upper Cretaceous strata bevel the Knoxville.

FIG. 5.—Geology at beginning of Tertiary. The Franciscan area shown south of Coalinga needs confirmation. Elsewhere the symbols indicate the age of rock upon which the Tertiary blanket lies. Compare Figure 17.

in print, have been examined by several geologists.[9] Martinez strata here rest on the beveled edges of the Chico and overlap it entirely toward the northeast. A few miles south of the line of overlap the two formations have nearly the same dip and may appear conformable.

Angular discordance between Upper Cretaceous and Eocene strata is observable here and there in the San Rafael and Diablo uplifts, but the absence of Martinez strata in these localities prevents accurate dating of the folding movements. Whatever the exact succession of events may prove to have been there is a great accumulation of evidence tending to show that the San Rafael and Diablo uplifts were folded, uplifted, and largely eroded to sea-level between some time very late in the Cretaceous and the middle of the Eocene. This disturbance is demonstrated not only by the distribution and character of the formations involved, but also by angular discordance and by overlap relations along the margins of both uplift areas. Details will be given in later chapters. The conclusion seems inescapable that a disturbance approximately contemporaneous with the Laramide orogeny of the Rocky Mountain region strongly affected the Coast Range province. By it the Mesozoic geosynclinal basins were altered to folded areas of uplift, the granitic provinces remained as weakly positive provinces, and the strongly negative areas of the Tertiary now came into existence as narrow embayments covering parts of the boundaries between uplifts and granitic provinces. Figures 5 and 6 will help explain the relations.

Cenozoic Epeirogeny

Paleocene basins and deposits

Following Stewart and others the writers assume that the Martinez formation is Paleocene. It may of course be Danian, as believed by some paleontologists, or it may not be a stratigraphic unit. Its faunas are poor in many exposures, and those from most localities are in need of more thorough study than they have yet had. The Martinez is found, commonly as conglomerate and sandstone, in the Santa Aña and Santa Monica mountains, on Santa Cruz Island, in the Simi Valley, in the mountains south of the south end of the San Joaquin Valley, and in a few places northwest of Coalinga. It is also reported from some localities along the west margin of the Salinas Valley.[10] Thicknesses in these several localities range from a few hundred to a few thousand feet.

[9] Among the men to whom the writers are indebted for information on this area are Alex Clark, R. W. Burger, Réné Engel, and J. C. Sutherland.

[10] M. G. Edwards, "Some Eocene Localities in Salinas Valley District, California," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 17, No. 1 (January, 1933), p. 81.

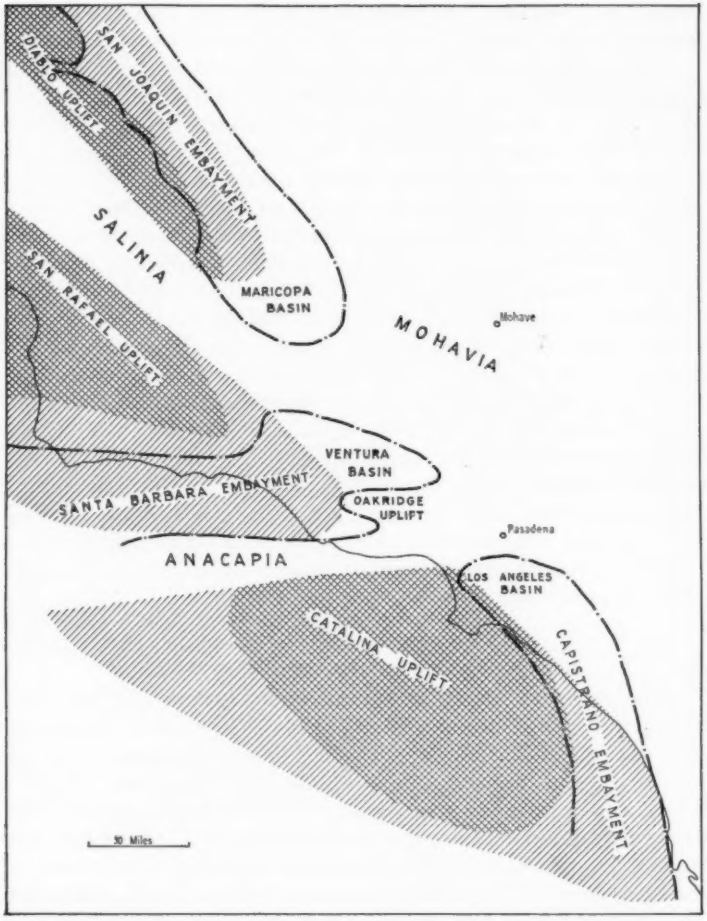

FIG. 6.—Geologic provinces of the Tertiary. Cross-hatched areas are Franciscan areas that became uplifts at end of Mesozoic; hachured areas are also underlain by Franciscan, but continued negative. The blank areas are underlain by granitic basement. This map is the most important of all for an understanding of the thesis of this book.

Except in the Coalinga region, deposits of the Martinez Sea are not found in the old geosynclinal areas. The sea left deposits on western Salinia (Salinas Valley), east of the Central Geosyncline (Simi Hills), on Anacapia (Santa Cruz Island), and northeast of the Southern Geosyncline (Capistrano region), but not, so far as known, within the limits of either the Central or Southern Geosyncline. That this avoidance of the geosynclines is real, however, is not at all certain. As already explained, the Diablo and San Rafael uplifts probably came into existence about the end of the Cretaceous and were not re-submerged until the Middle Eocene. If the Martinez Sea invaded the Central Geosyncline, it was thus probably restricted to the part which lies south of the present course of the Santa Ynez River, in which only younger beds are now exposed. If it invaded the Southern Geosyncline, which is likely from the fact that Martinez deposits exist on Santa Cruz Island and east of Los Angeles Basin, our failure to find the record may likewise be due to inaccessibility of most of the area. However this may be, the Martinez as it is known at present is chiefly a littoral deposit of southwestern Mohavia and the two peninsulas.

In addition to Figure 7, which furnishes distributional and thickness data of the kind shown on the other paleogeographic maps, Figure 8 has been prepared as a frankly speculative reproduction of the landscape and seaways of Southern California as they may have appeared at the beginning of the Tertiary period. This reproduction goes beyond the evidence, in the sense that several of its features cannot be demonstrated, but it is nevertheless believed to be consistent with all the facts known about the deposits of the Martinez epoch.

POST-PALEOCENE PRE-EOCENE FOLDING

That folding movements may have occurred between Martinez and Eocene epochs is suggested by the very considerable difference in the distribution of their deposits. Because of stratigraphic uncertainties, however, no example of an undoubted unconformity can be given at present. In the type locality of the Mar ·nez, Merriam found[11] apparent conformity. In the Simi Valley there seems to be no marked unconformity at the top of the formation, but in the upper beds classed as Martinez there are fossiliferous Martinez boulders of the algal limestone facies[12] that is absent from the Simi Valley but occurs

[11] John C. Merriam, "The Geologic Relations of the Martinez Group," *Jour. Geol.*, Vol. 5 (1897), p. 774.

[12] F. B. Tolman, personal communication.

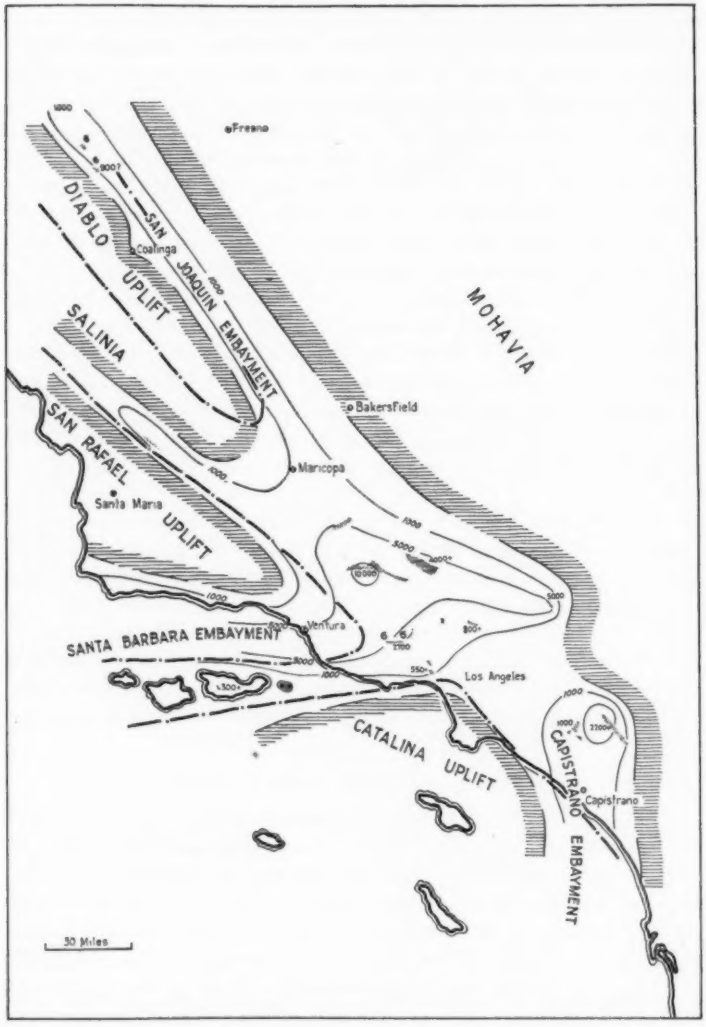

FIG. 7.—Martinez (Paleocene) paleogeography. Lands are shown by hachured borders; outcrops by stippling, thicknesses (in feet) by figures and isopachs. For the uncertainties attending Paleocene paleogeography, see text.

commonly in the Santa Monica Mountains, fifteen or twenty miles to the southeast, and may once have cropped out in the intervening San Fernando Valley. This occurrence clearly demonstrates differential movements of some kind, but whether or not they should be classed as orogenic is more than usually difficult to say.

EOCENE BASINS AND DEPOSITS

A summary account of earlier work on the Eocene and of the status existing five years ago may be found in the *Geology of California*. Since that account was written F. B. Tolman and others have greatly extended our knowledge of the distribution of the fossil mollusks and other larger invertebrates; Chester Stock has continued to secure mammalian fossils—correlated with the Upper Uinta and Ludian—from Simi Valley and elsewhere; and several micropaleontologists, among whom the writers are particularly indebted to B. C. Adams, have investigated more fully the occurrence and distribution of the *Foraminifera*. The work of these men has, in fact, progressed so far that it now seems possible, for the first time, to sketch in outline the succession of events in the development of Eocene basins of deposition in the Coast Ranges.[13]

Until about 20 years ago the whole Eocene series was named Tejon, to recall the fact that Eocene fossils had been recognized and described from a boulder about a cubic foot in volume which W. P. Blake found in Grapevine Canyon near the Tejon Ranch, and sent to T. A. Conrad in Philadelphia. After enough paleontologic work had been done in this locality and elsewhere to demonstrate that this section is incomplete, attempts began to be made to recognize, define, and name the stages that are missing here but present in some of the other Eocene localities. Among the names in common use at present are "Meganos," "Capay," "Domengine," and "Tejon," the last being used in a greatly restricted sense. These names, supplemented in all probability by a few others, are likely to prevail and eventually to become part of a comprehensive and satisfactory classification of California Eocene stratigraphy.[14]

In spite of this probability, the names are at present so indefinitely

[13] The writers are greatly indebted to F. B. Tolman, who furnished most of the correlations shown in the stratigraphic figures and tables. He has in preparation a paper that will describe in detail the Simi Valley Eocene section, and will give the paleontological evidence upon which his—and our—correlations and conclusions are based.

[14] The most recent discussion of this subject, which appeared after this chapter was written, is "Summary of Marine Eocene Sequence of Western North America," by B. L. Clark and H. E. Vokes, *Bull. Geol. Soc. America*, Vol. 47 (1936), pp. 851–78.

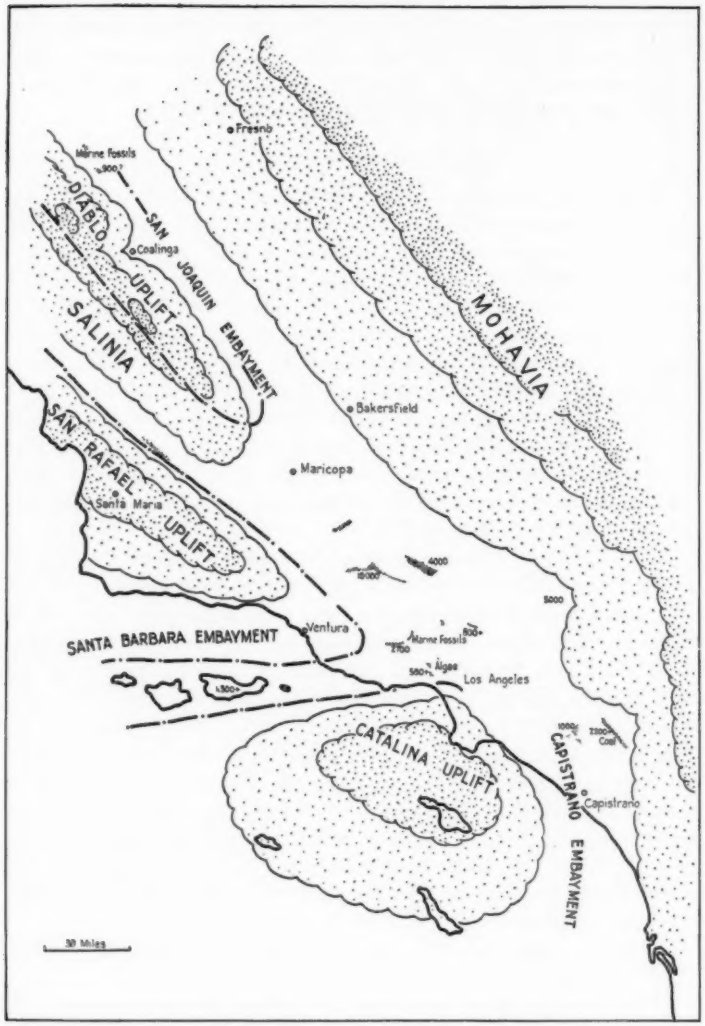

FIG. 8.—Martinez topography, a speculative restoration. Drawn to show the writers' conception of the structural importance of the orogenic disturbances at the close of the Mesozoic era.

applied in many localities, and have been used in so many different senses that it has seemed better to avoid them or to use them only in the local areas to which they particularly apply. In their place it has seemed better to use the terms Lower, Middle, and Upper Eocene, and to divide each of these groups into an upper and a lower division. In order to avoid frequent use of such expressions as "Upper Upper Eocene," the writers occasionally use, with quotation marks, some locality terms that may be found in Table II. In selecting these for

TABLE II

CLASSIFICATION OF EOCENE STRATA

UPPER EOCENE
- Upper Upper Eocene—"Coldwater beds." Fossiliferous, Ojai district
- Lower Upper Eocene—"Grapevine Canyon beds," equivalent to the greater part of the strata now commonly included in restricted Tejon

MIDDLE EOCENE
- Upper Middle Eocene—"Upper Llajas beds," partly equivalent to the Domengine of Clark
- Lower Middle Eocene—"Lower Llajas beds," more or less equivalent to the Capay of current usage

LOWER EOCENE
- Upper Lower Eocene—"Upper Santa Susana beds," equivalent to a part of the type Meganos (Meganos D) of Clark
- Lower Lower Eocene—"Lower Santa Susana beds," more or less equivalent to beds called Upper Martinez and to others called Lower Meganos in different sections

purely temporary use they have tried to avoid names that might appeal to others for general use. Their wish is merely to give at present, without waiting for the evolution of an adequate nomenclature, an intelligible discussion of the paleogeography and geologic history of the California Eocene, and they hope to avoid setting up any stratigraphic terms of such formality as to require attention from succeeding writers. Their divisions are not formal stages, zones, or even formations, and their terms are purposely put in a form that is old-fashioned and deserving of disapproval by serious workers in stratigraphy.

In addition to the correlations suggested by the table, it is worth noting here that nearly if not quite all the Eocene occurrences of glass sand, pottery clay, and workable coal beds, and all the more important limestone lenses such as the Sierra Blanca, belong in the Middle Eocene, and that the majority come near the boundary between lower and upper Middle Eocene. Thus the glass sand is commonly found near the top of lower Middle Eocene, while the Sierra Blanca type of limestone often occurs at the base of upper Middle Eocene (Figs. 9 and 10).

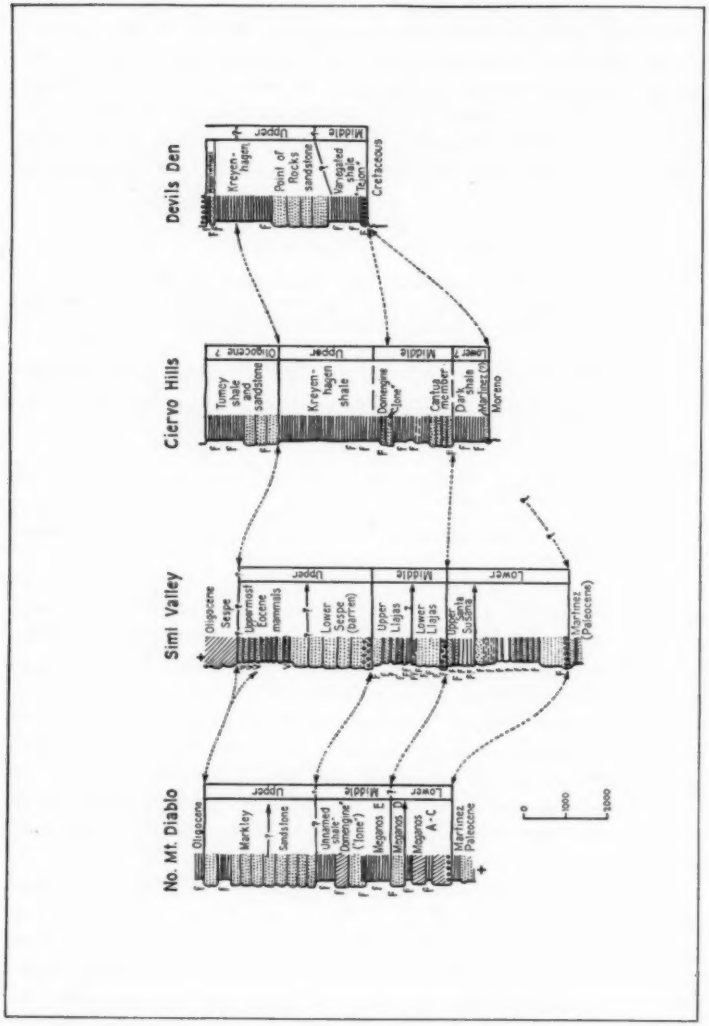

FIG. 9.—Columnar sections of Eocene strata.

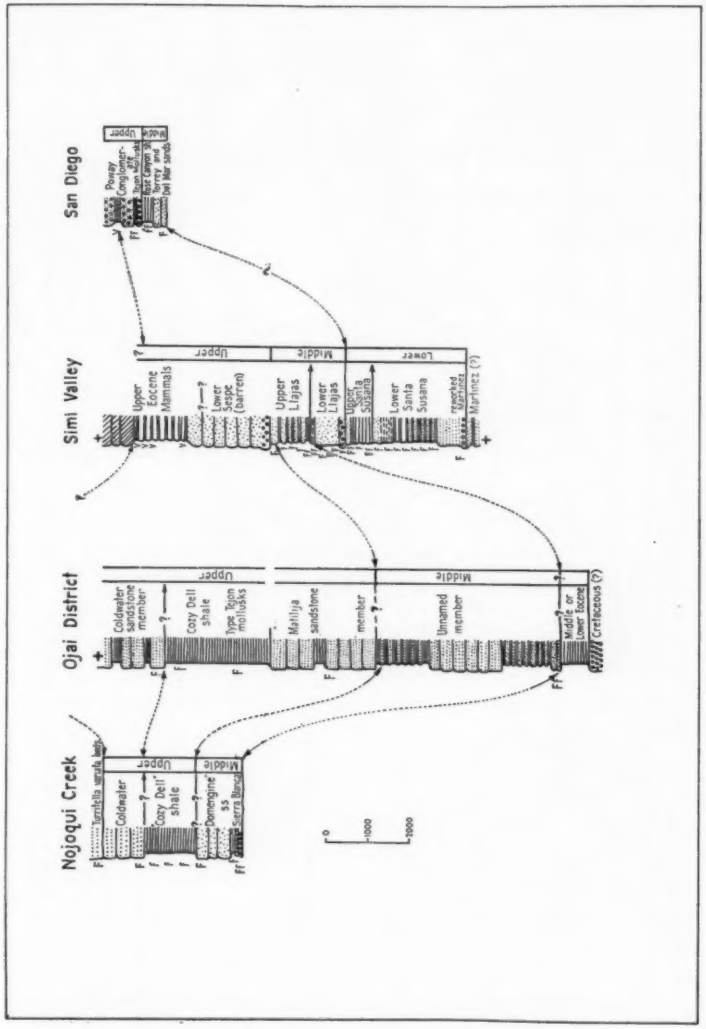

FIG. 10.—Columnar sections of Eocene strata.

TABLE III

CORRELATION OF EOCENE STRATA

		Simi	*Ojai*	*San Diego*	*Gaviota*	*Grapevine*	*Devils Den*	*Ciervo Hills*	*North Mt. Diablo*
UPPER	Coldwater beds	Lower Sespe Mammal horizons	Coldwater sandstone	Upper Poway conglomerate	Coldwater sandstone	Uppermost shale, Little Tecuya Canyon	Uppermost Kreyenhagen	Upper Kreyenhagen	Upper Markley
	Grapevine Canyon beds	Barren basal Sespe (?)	Cozy Dell	Lower Poway conglomerate	Cozy Dell	Tejon	Point of Rocks sandstone?	Middle Kreyenhagen?	Lower Markley sandstone
MIDDLE	Upper Llajas beds	Upper Llajas beds	Matilija	Rose Canyon shale	Unnamed sandstone Sierra Blanca limestone		"Tejon" fossil beds and overlying shale	Lower Kreyenhagen and Upper Domengine	Shale at Nortonville
	Lower Llajas beds	Lower Llajas beds	Unnamed series	Del Mar sand				Domengine	Domengine
								Unnamed shale	Ione sandstone
				Torrey sand				Cantua sandstone (base)	Meganos E
LOWER	Upper Santa Susana beds	Upper Santa Susana beds	Basal beds					Basal shale (?)	Meganos D
	Lower Santa Susana beds	Lower Santa Susana beds							Meganos A-C
	Martinez	Martinez or Cretaceous	Cretaceous	Schist	Cretaceous	Granite	Cretaceous	Cretaceous	Martinez

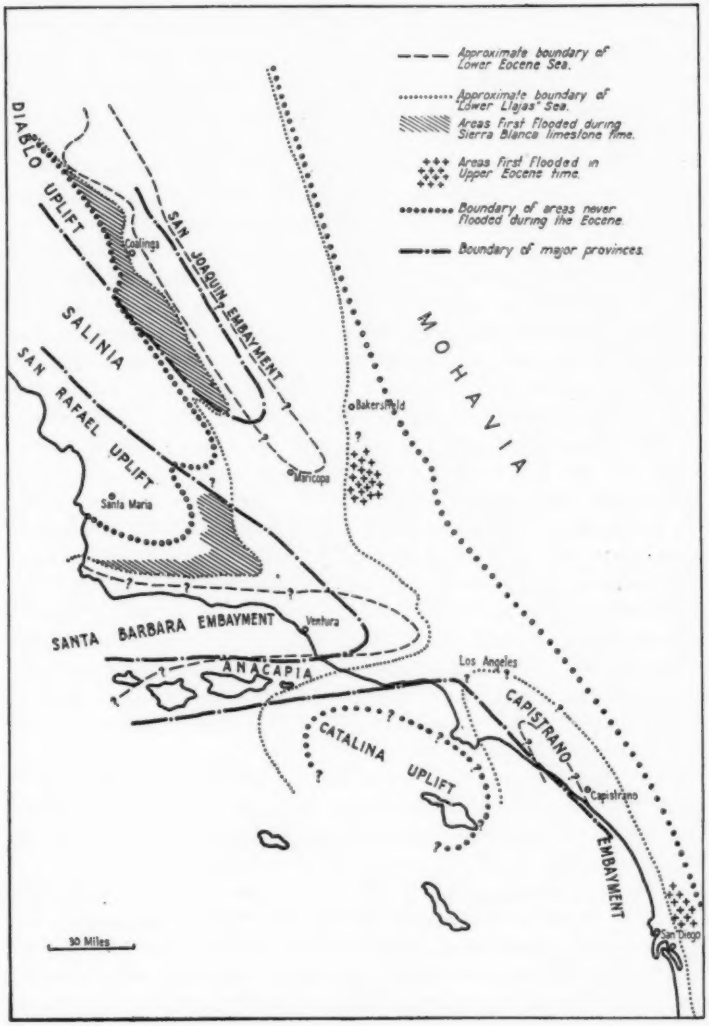

FIG. 11.—Boundary of the sea at different stages of the Eocene.

Table III shows how the Eocene strata of several important sections fall into the divisions of the list given in Table II. Only two localities, one of them in Middle California, have all the divisions clearly represented. The others seem to lack all or part of the Lower Eocene. Two sections even begin with the lower member of the upper Middle Eocene, the Sierra Blanca limestone horizon. Others begin with slightly earlier strata belonging to some part of the lower Middle Eocene. Only one of the sections given has no Eocene strata earlier than Upper Eocene, but, as Figure 11 shows, similar conditions also exist in a part of the area northeast of San Diego.

Figure 11 is designed to bring out some other facts of distribution that are interesting and perhaps important. It shows, for example, that Lower Eocene strata are definitely known only in the San Joaquin and Santa Barbara embayments and suggests that they may underlie all the more central parts of those embayments. Nothing is known at present of conditions in the central part of the Capistrano embayment. The map shows, further, that lower Middle Eocene beds lie upon granite east of the San Joaquin embayment (as the "Ione" sequence) and east of the Los Angeles embayment (Torrey and Del Mar sands). They are also found locally upon the Cretaceous along the flanks of the Diablo and San Rafael uplifts. Upper Middle Eocene beds occur with the lower Middle Eocene near San Diego, but are not certainly recognized in the Sierra Nevada foothills; on the other hand, they extend far beyond the limits of the lower Middle Eocene in parts of the San Rafael and Diablo uplifts. The only places, finally, where Upper Eocene transgresses so as to lie upon pre-Eocene rocks are, first, near Grapevine Canyon in the southeast end of the San Joaquin Valley (type Tejon) and second, in an area northeast of San Diego (Poway conglomerate).

The Eocene formations are as diverse lithologically as the later series belonging to the Coast Range Tertiary. They include marine and nonmarine members, conglomerate, sandstone, argillaceous and siliceous organic shale, bentonitic beds, and limestone lenses. It is worth noting, however, that in spite of this diversity the earlier geologists, who called all the Eocene formations "Tejon," were much impressed by the quantity of white sandstone in the series, and also by the character of the fossiliferous "reef beds," which are either calcareous sandstones or more or less sandy or pebbly limestones. It should also be noted that with the probable exception of a few Martinez occurrences, all of the glass sand deposits of the State belong to the "Tejon" in the old sense, and to the Middle Eocene of the present discussion.

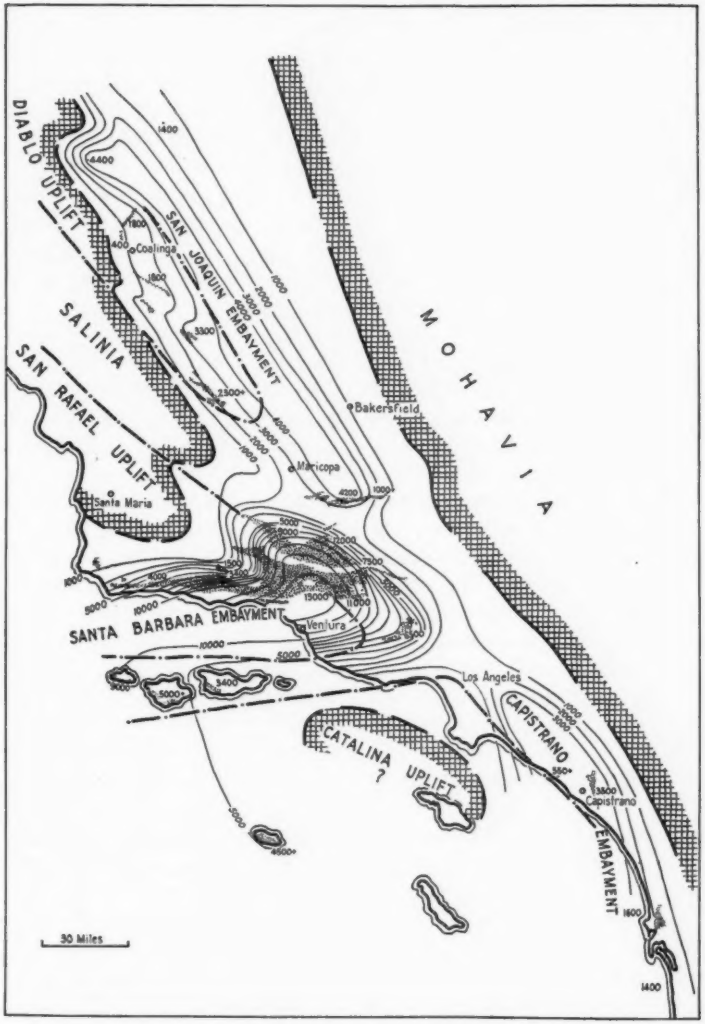

FIG. 12.—Eocene paleogeography. Symbols as in Figure 7. Note the amount of subsidence of the Ventura Basin.

This Middle Eocene quartz sand and associated white sands of more feldspathic type often occur with coal beds, as already pointed out, and occasionally with pottery clays. They belong, in general, to the upper part of the division here called the "Lower Llajas beds," or lower Middle Eocene. Associated floras have demonstrated that the lands of "Lower Llajas" time were covered with a forest related in type to that which now lives in southeastern Asia and the East Indies. There is thus an accumulation of evidence tending to confirm Allen's suggestion[15] that the quartzose character of the "Ione" is due to the existence during the earlier Eocene of a period of exceptionally thorough chemical weathering. The soils upon the lands at that time were leached of everything except such highly resistant minerals as certain clays, quartz, gold, and a few heavy minerals.

We thus picture the California of the earlier Eocene as a jungle-covered low land bordered by a broad, shallow sea in which there were some forest-covered islands, also of low relief. The sluggish streams from mainland and islands may be supposed to have brought down clays, silts, and fine sands, but to have permitted coarser materials to accumulate on the lands and to be subjected for ages to the chemical decomposition characteristic of such a climate and such topography. Toward the end of Middle Eocene time the hitherto steadily widening seas were shallowed and restricted and the lands were arched upward. The rejuvenated streams at first had little to work upon except accumulations of non-weathering substances such as quartz, gold, zircon, and great thicknesses of thoroughly weathered clayey soils.

After this regressive episode the seas expanded again and in the San Rafael and Diablo uplifts reached areas not previously flooded since the Laramide folding. The small areas remaining above water in these regions were apparently not high enough or extensive enough to furnish coarse detritus to many parts of the sea bottom. Where currents were strong enough to keep the sand and silt winnowed away, masses of shell fragments—the only coarse material available—accumulated to such an extent as to give rise to the Sierra Blanca limestone, which is thus in a sense a "basal conglomerate" and which in places grades into a more normal basal conglomerate. During the rest of the upper Middle Eocene, sand and silts accumulated in most parts of the sea and toward the end of this epoch the sea began to withdraw from some areas. In the Upper Eocene the uniform conditions of the Middle Eocene were greatly disturbed, though the evi-

[15] V. T. Allen, "The Ione Formation of California," *Univ. California Pub. Geol.*, Vol. 18 (1929), p. 402.

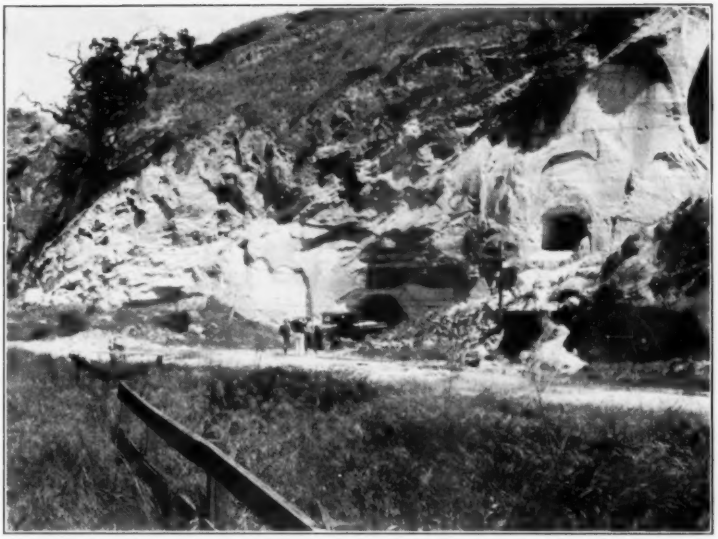

PLATE II-A.—Glass sand quarry in "Ione" member north of Mount Diablo.

PLATE II-B.—Eocene section of Ciervo Hills, with "Ione" member in middle distance.

dence available at present comes mainly from the nature of the sediments—conglomerate at San Diego, red beds in the Simi Hills, littoral sandstones at Grapevine Canyon, and siliceous organic shale at Coalinga—and not from any known unconformities of demonstrated importance.

The climate of the Upper Eocene seems to have remained warm and rainy, as shown by such criteria as the character of the mollusks, the occasional occurrence of orbitoids, and by the nature of the lower Sespe mammals, which are of forest-dwelling types.[16] This last point is of particular interest in view of attempts that have often been made to claim all red beds as desert deposits.

EOCENE FOLDING

Lower Eocene was thus a time of restricted seas, Middle Eocene of widespread transgression, and late Upper Eocene of a renewed regression. Several unconformities have been described in deposits representing these epochs but in coastal California at least, none seems to be demonstrably of much importance. Even in the Simi Valley, where the upper Middle Eocene Las Llajas beds are succeeded by nonmarine Upper Eocene red beds, there is no record of measurable angular discordance. In the Santa Ynez Valley, Middle Eocene seems to overlap Lower Eocene toward the north, but again there is no satisfactory evidence of unconformity. The known unconformities most likely to prove important occur about the margins of the San Joaquin Valley. Clark has described[17] one from near Coalinga, and another[18] from the San Emigdio district. Both of them are said to show evidence of slight folding. The former belongs within the Middle Eocene, the latter, perhaps, between Middle and Upper Eocene.

By the close of the Eocene the sea had withdrawn from nearly all of the California mainland. Throughout the ancestral Ventura Basin and about its margins nonmarine red beds were accumulating. The San Rafael area was uplifted anew and began to shed sediments toward the southeast. Part of the area of the present Los Angeles Basin was undergoing erosion, as were perhaps nearly all of Salinia and Anacapia, and most of Mohavia.[19] Only in the western part of the Central

[16] Chester Stock, "Evidence of Changing Climates during the Later Eocene and Oligocene of California," paper read before Cordilleran Section, Geological Society of America, April 18, 1936.

[17] B. L. Clark, "The Domengine Horizon, Middle Eocene of California," *Univ. California Pub. Geol.*, Vol. 16 (1926), pp. 99–118.

[18] B. L. Clark, "The Stratigraphic and Faunal Relationships of the Meganos Group, Middle Eocene of California," *Jour. Geol.*, Vol. 29 (1921), p. 150.

[19] As shown by the recent discovery of some Lower Oligocene titanotheres, a part

Geosyncline and in the central part of the Northern Geosyncline did marine deposition continue. On the San Rafael uplift erosion and recurrent elevation must have gone on apace, since the Franciscan rocks of this area contributed coarse detritus to upper Eocene and Oligocene basins. North of Coalinga Atwill and others have noted an erosion surface between Eocene and Oligocene, "together with the presence of the basal shale-pebble and cobble conglomerate in the overlying sandstone."[20]

There is thus some indirect evidence tending to show that important orogenic disturbances occurred at or near the end of the Eocene, but direct and indubitable evidence is hard to find. One difficulty is that the few areas most likely to furnish the desired evidence have been less carefully studied than they deserve to be; a related difficulty is that age determinations of Upper Eocene and Oligocene strata still leave much to be desired.

OLIGOCENE BASINS AND DEPOSITS

As Schenck has suggested,[21] there are many reasons for suspecting that much or all of the Lower Miocene of the Coast Ranges is contemporaneous with Middle and Upper Oligocene of other provinces. This suggestion is in harmony with the fact that the Oligocene as now recognized in California is generally thin, and that a considerable part of the supposed Oligocene of many areas is known to have close faunal relations with the Eocene. In the Sespe formation of Simi Valley, as noted already, the lower part has yielded Upper Eocene (Uinta) mammalian fossils; and in the southern San Joaquin Valley the *Uvigerina cocoaensis* beds, commonly referred to the Oligocene, are suspected by some paleontologists to be Eocene instead.

Since there is no evidence of a widespread Oligocene hiatus in the different California provinces, and since the beds recognized as Oligocene are thin and of Eocene aspect, the most probable conclusion seems to be that part or all of the beds commonly referred to Lower Miocene should be reclassified as Oligocene. That this reclassification is faunally not impossible has been urged by Schenck in the paper

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of Mohave Desert along the Nevada-California line, east of the present site of Death Valley, sank at this time and received accumulations of clastic nonmarine beds and volcanic rocks. Chester Stock and Francis D. Bode, "Occurrence of Lower Oligocene Mammal-Bearing Beds near Death Valley, California," *Proc. Nat. Acad. Sci.*, Vol. 21 (1935), p. 571–79.

[20] E. R. Atwill, "Oligocene Tumey Formation of California," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 19, No. 8 (August, 1935), p. 1197.

[21] H. G. Schenck, "What Is the Vaqueros Formation of California and Is It Oligocene?" *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 19, No. 4 (April, 1935), pp. 521–36.

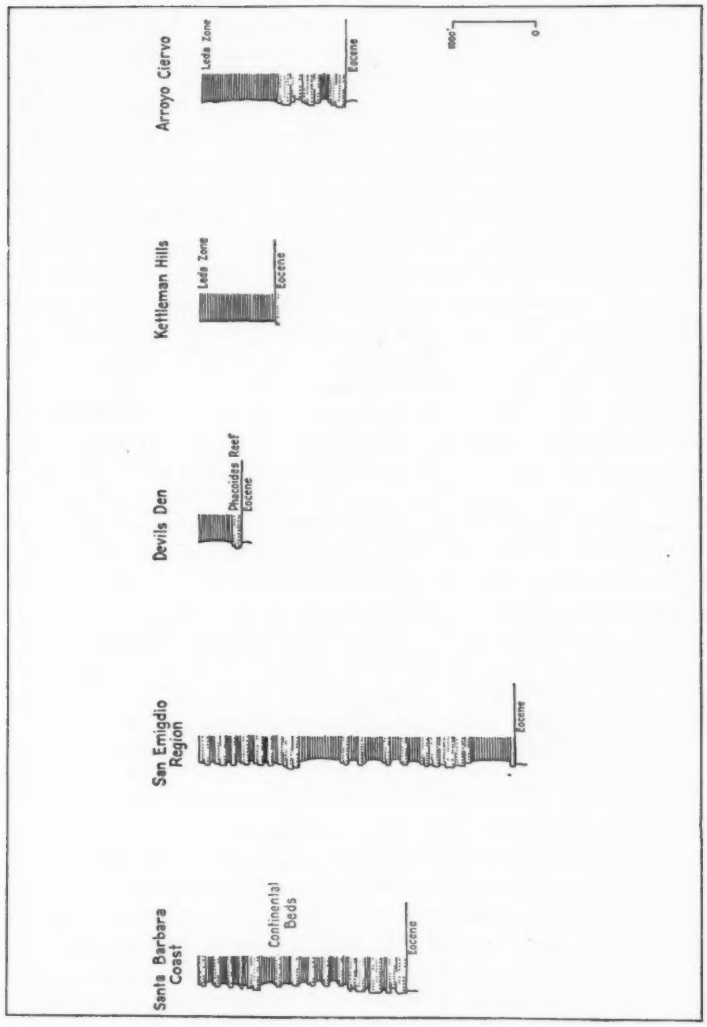


FIG. 13.—Oligocene columnar sections. The Sespe of the Ventura Basin is more than twice as thick as the thickest section shown here, but not all of it is Oligocene.

cited. Since the problems of interregional correlation do not closely concern the present discussion, however, the writers prefer to adopt the commoner correlation, and to discuss as Oligocene only the Coast Range strata to which that age has been ordinarily assigned in the past.

These beds belong to a period of marked marine regression. They are largely nonmarine, and even the marine deposits are so varied in facies as to be difficult to correlate with one another or with the type sections of other regions. Perhaps the most striking feature of Oligocene distribution is the occurrence in an expanded Ventura Basin of a great mass of red beds, the Sespe formation. The lower part of the formation is now known to be Upper Eocene, and the upper part is suspected to be equivalent to marine beds that are correlated with Lower Miocene. The formation is locally 7,000 feet thick, however, and thus even when the base and top are removed, it is thick as compared with other Oligocene formations in California (Fig. 14).

Sespe strata are found both east and west of the Los Angeles Basin, and may underlie its eastern margin. They appear to be absent from the Channel Islands, and are certainly absent from much of the San Rafael Mountain region. They occur in larger or smaller patches in Cuyama Valley and in the mountains farther east and south. Though well developed in the Santa Ynez Mountains, the Sespe thins and becomes marine, at least in part, toward its western end.[22] Other marine strata of Oligocene age are found only in the hills at the south end of the San Joaquin Valley and in some localities north and south of Coalinga along the west side of the Valley.[23] These strata range in facies from coarse-grained littoral deposits at the south to organic siliceous shale near Coalinga; in thickness from more than 3,000 feet in the former locality to a maximum of 1,600 feet in the latter.

OROGENIC DISTURBANCES DURING THE OLIGOCENE

Near the close of the Oligocene a new area of uplift, the Oakridge uplift, came into existence in the southeastern part of the old Ventura Basin. The exact history of this event is made uncertain by the scarcity of fossils in the upper Sespe and the resulting uncertainty as to the exact sequence of events between middle Sespe time and the beginning of marine Vaqueros deposition. It is nevertheless clear that the area of the Oakridge uplift subsided rapidly during Eocene and Oligocene and then became an area of slow and uneven subsidence

[22] H. G. Schenck and R. M. Kleinpell, "Refugian Stage of Pacific Coast Tertiary," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 20, No. 2 (February, 1936), pp. 215–25.

[23] E. R. Atwill, *op. cit.*, pp. 1192–1204.

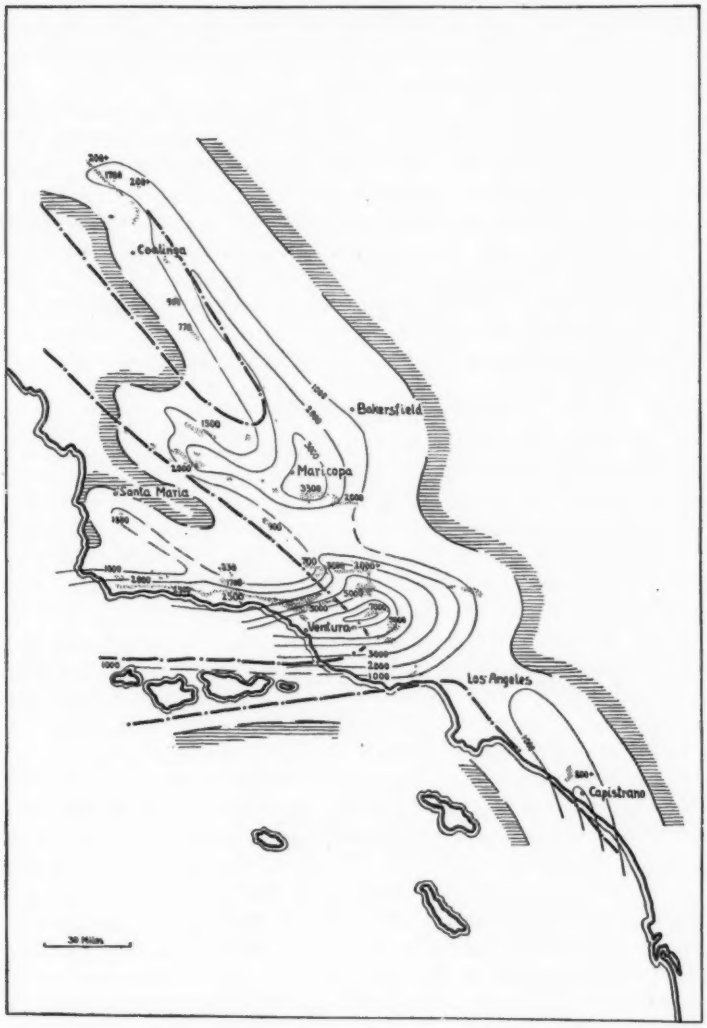


FIG. 14.—Oligocene paleogeography. Symbols as before. Some of the red beds discussed as possibly or certainly Miocene or Eocene in the text are included in this map as Oligocene.

often interrupted, during the later Tertiary. An examination of the paleogeographic maps will make the matter reasonably clear. Further details are given later, in connection with the account of the development of the modern Ventura Basin.

Another event that may date from about the same time is the beginning of rapid subsidence in the area of the Caliente trough. The problems connected with this event are also discussed later, in the account of the Caliente Mountain area.

In summary, the relatively short period now called Oligocene in California was in all probability a time of important diastrophic events in the Coast Ranges, but present knowledge of these events is still meager and unsatisfactory. The investigations of the next few years may enable geologists to unravel the details of a complex and interesting history that we do not fully understand at present.

MIOCENE BASINS AND DEPOSITS

The Miocene of California (Fig. 16), is thick, widespread, variable, and important from many points of view. Because of its wealth of fossils of the most varied kinds, and of its outstanding economic importance, its stratigraphy and paleogeography are now well known. The series is thus a very important one from the point of view of structural history. For present purposes it may be divided into Lower (Vaqueros and part of the Temblor, Rincon, and others), Middle (part of Modelo, Monterey, Temblor, Topanga, Maricopa, and several others), and Upper (San Pablo, Santa Margarita, McLure, part of Monterey, Maricopa, Modelo, and many others). Since few of the names in parentheses are definite except when used locally, they will be disregarded for the most part in the subsequent discussion.

The Miocene has been zoned on the basis of several different kinds of fossils, but the most useful zoning at present is that of the foraminiferal workers. About 15 foraminiferal zones are now recognized and used in connection with the Miocene of Southern California, and most of them are known to extend far beyond the borders of the province. To furnish an idea of the type of classification they permit, the zones currently in use in the paleontological laboratory of The Texas Company may be listed (Table IV). Other foraminiferal workers accept a similar classification, but differ more or less in their use of zone names. As is natural, also, some workers choose to split some of the zones here listed as units, or to lump together two of those here considered separate.

That these zones represent equal periods of time is highly improbable; yet, taken together, they seem to represent practically the

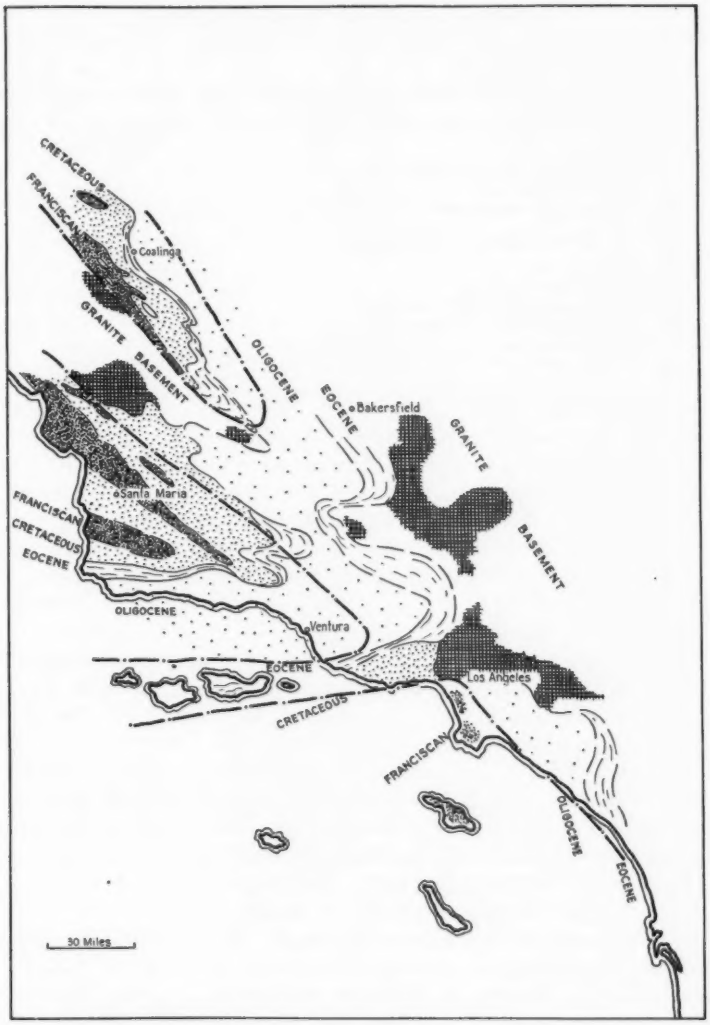


FIG. 15.—Geology at end of Oligocene. Note that structural complexity seems to have increased greatly since the beginning of the Tertiary, in spite of the fact that major unconformities have not been recognized in the Eocene-Oligocene strata.

TABLE IV

FORAMINIFERAL ZONES OF CALIFORNIA MIOCENE

UPPER MIOCENE
1. *Bolivina seminuda* zone
2. *Bolivina hughesi* zone
3–4. *Bulimina uvigerinaformis* and *Baggina californica* zones (not always separable)

Horizon of profound discordance of Santa Monica Mountains

MIDDLE MIOCENE
5. *Valvulineria californica* zone
6. *Baggina robusta* zone
7. *Siphogenerina hughesi* zone (="button bed" of Temblor Mts.)

Strong faulting of San Joaquin Hills

LOWER MIOCENE
8. *Uvigerinella obesa* zone
9. *Plectofrondicularia miocenica* zone
10. *Haplophragmoides trullissata* zone
11–12. *Bolivina marginata* var., and *Siphogenerina transversa* zones
13–14. *Cibicides americanus* and *Cancris sagra* zones

Horizon of "Vaqueros sandstone" of Santa Barbara district

whole of the time during which the California Miocene accumulated. It is thus interesting to recall that estimates of the length of Miocene time have ranged all the way from a few hundred thousand years to 15 million years. On the larger and more recent estimates each of the 15 zones may therefore be imagined to represent approximately a million years. If the Lower Miocene is to be considered Oligocene, however, the time represented by a zone may be nearer 2 million years.

The Lower Miocene (Fig. 17) occurs in the hills southeast of Los Angeles Basin as conglomerate, sandstone, and sandy shale and is presumed to underlie much of the Basin but is absent from at least its western edge and from the eastern half of the Santa Monica Mountains. It is thick and coarse on Santa Cruz and Santa Rosa Island (Anacapia), thicker but dominantly fine-grained in what remained of the Ventura Basin. It is thin and discontinuous over the western half of Salinia, but is several thousand feet thick in a long, narrow trough which lies parallel to the length and near the axis of this peninsular mass. On Caliente Mountain, which is near the southeast end of this trough, the Lower Miocene is littoral; farther southeast it becomes nonmarine. It is apparently absent from the Mohave Desert, but may be represented by some of the beds that have not yielded fossils. In the area of the Northern Geosyncline, Lower Miocene strata are thin or absent north of the latitude of Coalinga, but thicken southward and become several thousand feet thick in the hills southeast of Maricopa. Beds of the same age and facies as these at Maricopa are found in a small area along Cuyama River a few miles northeast of Santa Maria.

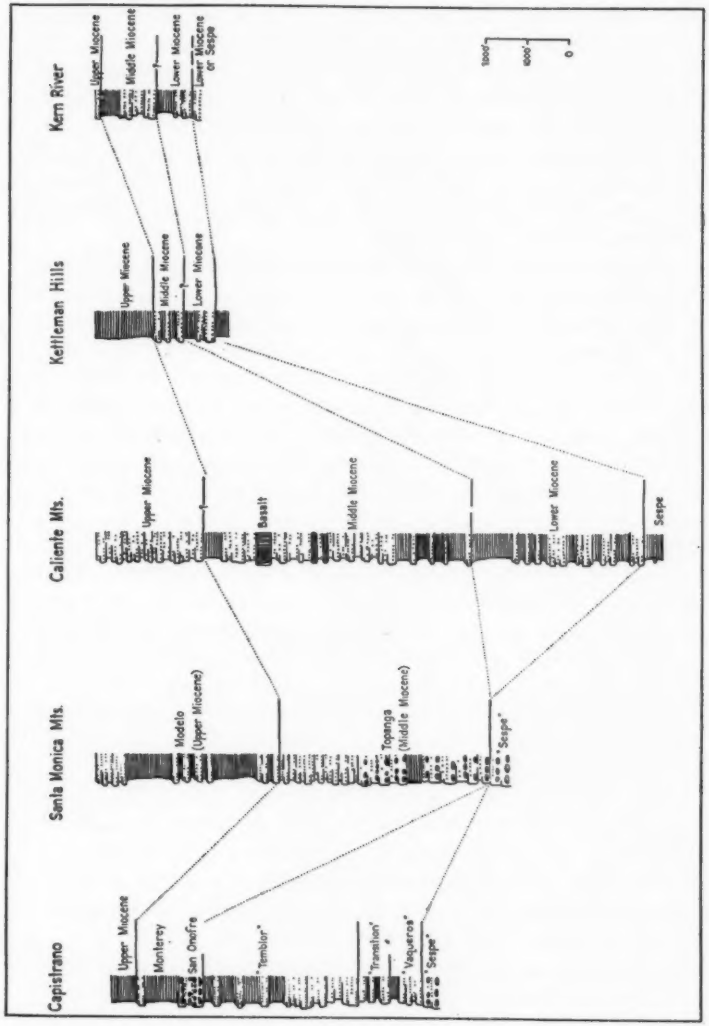


FIG. 16.—Miocene columnar sections.

In summary, the Lower Miocene represents a time of transgression after the great regression of the Oligocene. The Vaqueros sandstone, which probably may represent any stage of the Lower Miocene or all of it, was the initial deposit of the transgressing sea. Lower Miocene deposits occur in all the old basins, and in a few new ones such as the Caliente trough. They avoid the San Rafael and Diablo uplifts, and are very thin on the new Oakridge uplift. On the other hand they are found on the old positive areas not only in the western and central parts of the Salinas Valley region, but also near Bakersfield, on the Santa Barbara islands, and in the San Juan Capistrano area east of the Los Angeles Basin.

Toward the end of the Lower Miocene there was an outbreak of vulcanism in many areas (Fig. 18). In others, the earliest Miocene vulcanism dates from the beginning of the Middle Miocene. As explained elsewhere,[24] the end of the Lower Miocene saw a breaking up of the well-integrated drainage system that had been eroding Mohavia more and more deeply since the Jurassic period. The development of basins that took place at this time was certainly associated with faulting in some places, and perhaps in many. The apparent interrelations of the faulting, vulcanism, and following transgression will be discussed later.

Middle Miocene strata are very widespread in Southern California, and are commonly associated with volcanic products. Figure 19 illustrates the conditions in several areas. In facies, the strata range from organic siliceous siltstone to coarse, angular conglomerate and agglomerate. As compared with the Tertiary deposits of other stages, however, they impress everyone by their uniformity of facies. Even in localities where coarse deposits predominate it is not unusual to find intercalations of the highly foraminiferal siltstone of the "Gould shale" and "*Valvulinera* beds."

Middle Miocene strata occur wherever the Lower Miocene is found and in several additional areas. They are found, for example, in the eastern part of the Santa Monica Mountains; they remain as outliers in many parts of the San Rafael and Diablo uplifts; and they occur in nonmarine facies in many Mohave Desert basins, where they commonly lie upon Jurassic or earlier rocks.

The thickness of Middle Miocene strata ranges from a few hundred feet to more than 5,000 feet. Owing to their lithologic similarity to some facies of the Upper Miocene, to the frequent scarcity of fossils in Upper Miocene strata, and to incomplete investigations, it is not yet possible to separate Middle and Upper Miocene strata sharply

[24] R. D. Reed, *Geology of California*, p. 186.

FIG. 17.—Lower Miocene paleogeography. Symbols as in previous paleogeographic maps.

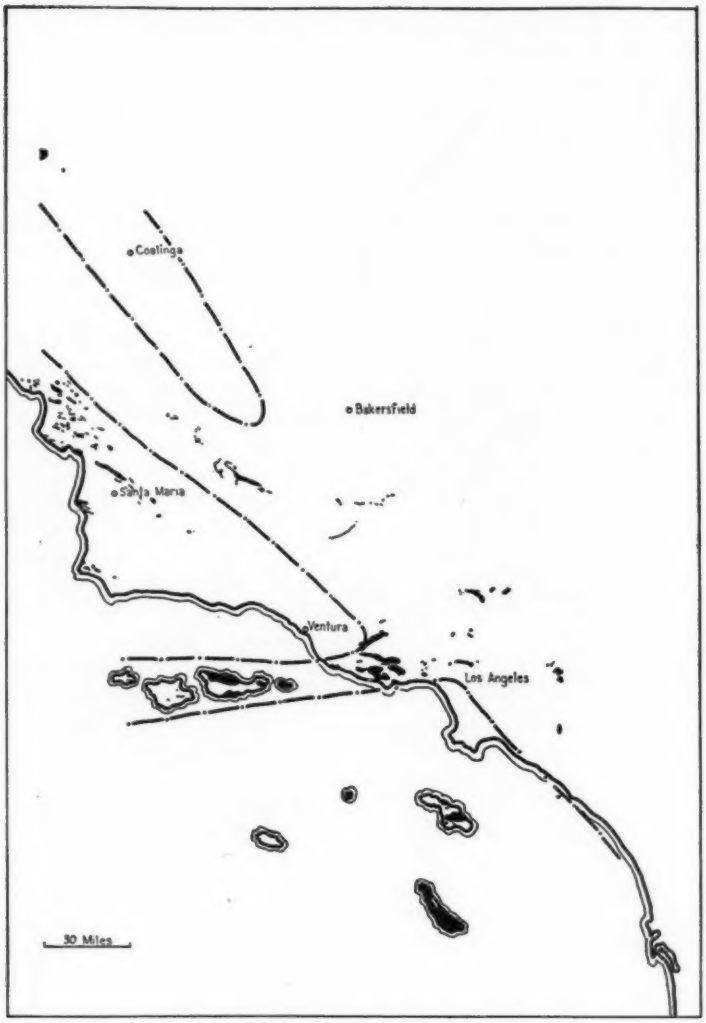


FIG. 18.—Distribution of Miocene volcanic rocks. Note their avoidance of the greater basins.

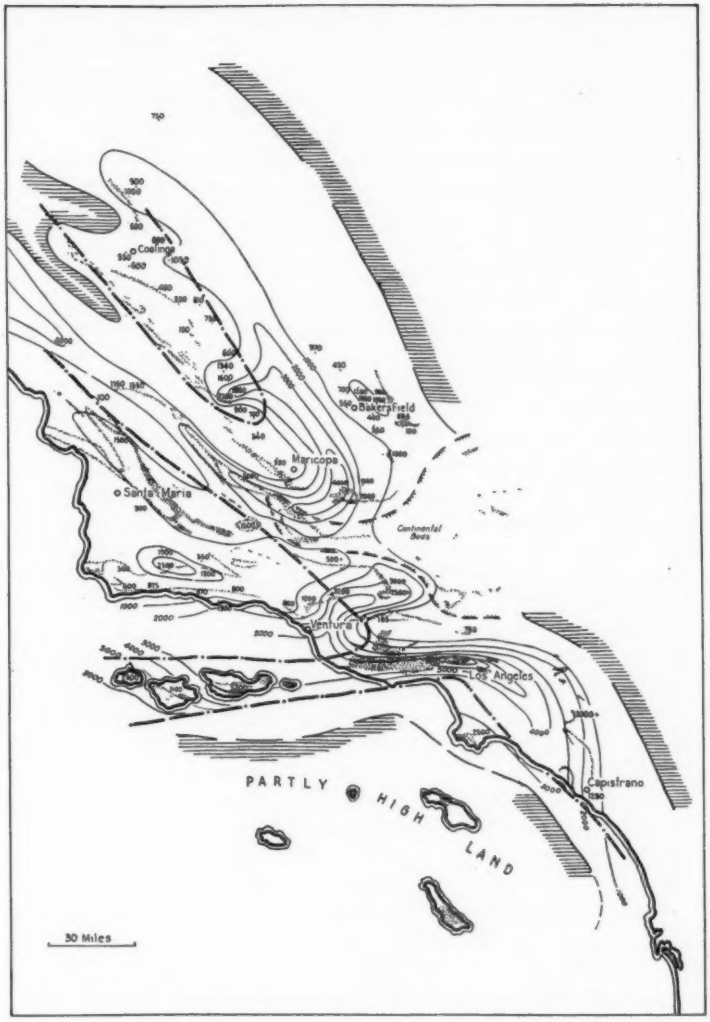


FIG. 19.—Middle Miocene paleogeography. In the narrow Caliente trough, west of Maricopa, several more isopachs would be necessary to show the full thickness of the Middle Miocene. See Figure 16.

in all localities. Some of the thickness figures of Figure 19 are therefore not as accurate as could be wished. They serve well enough to furnish a general notion of the distribution of the Middle Miocene, but several of them will undoubtedly be changed by future work. For the reasons just stated, the figures showing thicknesses of the Upper Miocene (Fig. 20), are also to some extent inaccurate.

In view of the relative intensity of the folding that locally affected Middle Miocene strata before the deposition of the Upper Miocene, it is remarkable that the two so nearly coincide in distribution, and even in thickness. There are also some similarities in facies, but those of the Upper Miocene are much less uniform. Indeed, the heterogeneity of facies, often considered a general trait of the California Tertiary, reached an extreme during the Upper Miocene. Conglomerate, diatomite, coarse white sandstone, and chert are some of the commonest lithologic types, but many others are found.

A comparison of the coarse detritus of Middle and Upper Miocene also reveals the fact that the former is largely of Franciscan origin, the latter dominantly granitic. The Middle Miocene San Onofre breccia and Big Blue serpentinous member, both described in some detail later, contrast strikingly with the coarse granitic Santa Margarita sands and conglomerates found here and there in the Upper Miocene (Fig. 21). Even when the Santa Margarita lies upon the Franciscan, as it does in several places, it is either a coarse granitic detrital series or fine-grained siliceous shale. These interesting facts are most readily explained on the hypothesis that the apparently tensional diastrophism of the beginning of the Middle Miocene affected chiefly the Franciscan areas, while the later, apparently compressional disturbances chiefly affected the granitic areas. Perhaps the change from dominantly basaltic to dominantly andesitic vulcanism between Middle and Upper Miocene is in some way related to this difference in the site and nature of diastrophic activities. In any event, the whole problem seems worthy of thorough investigation for the light it may throw on some fundamental principles of tectonics.

Many of the supposed Upper Miocene nonmarine strata that have been described from the Mohave Desert region are now being reclassified as Middle Miocene. The Barstow beds, for example, with their *Merychippus* fauna, are probably not much younger than the *Merychippus* zone of Coalinga which contains a Middle Miocene marine fauna. The typical fossil horse of the Ricardo, on the other hand, is now turning up in beds that carry marine faunas hitherto classed as Upper Miocene.[25] For the present, therefore, the Lower Pliocene of

[25] Francis D. Bode, "The Fauna of the Merychippus Zone, North Coalinga District, California," *Carnegie Inst. Washington Pub. 453* (1935), pp. 63–96.

FIG. 20.—Upper Miocene paleogeography.

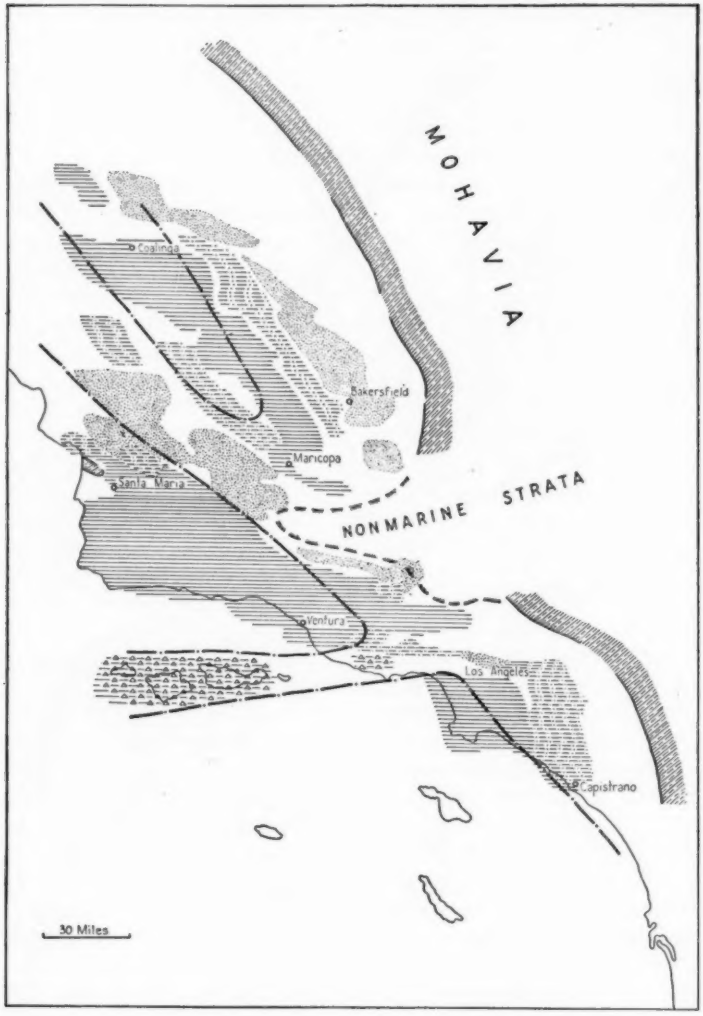


FIG. 21.—Upper Miocene facies. Shales are indicated by hachures, sandstone and conglomerate by stippling, agglomeratic material by dashes and triangles.

most vertebrate paleontologists[26] is at least in part the equivalent of the Upper Miocene of the invertebrate paleontologists. Since most of the beds under discussion here are marine, it has seemed better to call them Upper Miocene, according to the usual view, than to introduce a drastic change. This point will be mentioned again in the discussion of the Ricardo beds of the Mohave Desert region.

MIOCENE OROGENIC PHASES

Because of recent stratigraphic accomplishments, the diastrophic history of the Miocene is better known than that of any other Tertiary epoch. For this reason it must be discussed in some detail.

During the Lower Miocene there seems to have been little, if any, diastrophism of a distinctly orogenic character. In this connection it should, however, be noticed that the several Lower Miocene foraminiferal zones now recognized have been found in comparatively few places. In other places the strata are too coarse to yield good foraminiferal assemblages, though some of them yield excellent megascopic faunas. When the exact correlation of foraminiferal and molluscan faunas becomes better known, the history of the time will become clearer in detail and a record may be found of events not now suspected. The only diastrophic disturbances now recognized were related to the general outbreak of vulcanism that took place within the Lower Miocene in some localities, at its close in others. So far as can be determined at present, Lower Miocene vulcanism was in general tentative and premonitory, a sort of preparation for what was to come during the Middle Miocene.

The disturbance that closed the Lower Miocene was profound, widespread, and probably complex. Though it involved local uplift and erosion, it seems in most areas to have caused mainly a lowering of the lands and a shallowing of the seas. In at least one locality (Fig. 45) it involved extensive high-angle faulting, apparently tensional in type. As noted above, it came near the beginning of a period of exceptionally widespread vulcanism and was followed almost immediately by a great marine transgression. The disintegration of the Early Tertiary drainage system on Mohavia and the development of the many separate basins of Miocene deposition in that region were

J. C. Merriam and Chester Stock, "Tertiary Mammals from the Auriferous Gravels near Columbia, California," *ibid., Pub. 440* (1933), pp. 1–6.

[26] P. Teilhard de Chardin and R. A. Stirton, "A Correlation of Some Miocene and Pliocene Mammalian Assemblages in North America and Asia with a Discussion of the Mio-Pliocene Boundary," *Univ. California Pub. Geol.*, Vol. 23 (1934), pp. 277–90.
G. G. Simpson, "Glossary and Correlation Charts of North American Tertiary Mammal-Bearing Formations," *Bull. Amer. Mus. Nat. Hist.*, Vol. 67, Art. 3 (1933), Figs. 2, 7, *et cetera*.

manifestations of the same period of disturbance. The rhyolitic outbreaks of the Sierra Nevada were almost certainly going on, and may have begun, about the same time. Even in coastal California many new basins of deposition seem to have been developed by this disturbance. In Humboldt County, for example, the oldest known Tertiary *Foraminifera* are basal Middle Miocene.[27] In the northern Great Basin the beginning of the Columbia lava flows may also have come at this time.

In a few places such as the North Coalinga district there are indications of locally strong disturbances within the Middle Miocene, but none is demonstrably of much regional significance. Even the disturbance that closed the Middle Miocene, though in some localities more definitely orogenic than any other known Tertiary disturbance, left little clear record of its existence in other localities. In many regions, such as the Santa Maria district, the "Monterey shale" includes both Middle and Upper Miocene, and in some the boundary between the two is still poorly located. Even in the Salinas Valley where a pre-Santa Margarita disconformity has been widely recognized and discussed, no break of any kind has been recognized in some well-exposed sections.

The folding at this time was especially strong in the mountains east and west of the Los Angeles Basin.[28] The youngest folded beds in each case are "Topanga"; that is, at least as young as lower Middle Miocene and in all probability younger. The oldest beds above the discordant contact are in each case lower Upper Miocene. There is thus reason to suspect that the disturbance was very short-lived; in fact that it may have run its entire course in less time than that represented by an average foraminiferal zone. If the Miocene epoch is assumed to have lasted 15 million years or thereabouts, the post-Topanga orogeny may have lasted only a few hundred thousand years, or perhaps less.

In spite of the fact that this disturbance was locally strong and that its general effects were sufficiently great to replace the homogeneous facies of the Middle Miocene by the heterogeneous facies of the Upper Miocene, it had surprisingly little effect, as noted already, in displacing the boundaries of the Middle Miocene basins of deposition.

[27] J. A. Cushman and R. E. and K. C. Stewart, "Tertiary Foraminifera from Humboldt County, California," *Trans. San Diego Soc. Nat. History*, Vol. 6, No. 2 (1930), especially Pl. 5.

[28] For the conditions in the Santa Monica Mountains, see H. W. Hoots, "Geology of the Eastern Part of the Santa Monica Mountains," *U. S. Geol. Survey Prof. Paper 165-C* (1931), Pl. 22 B, *et cetera*.

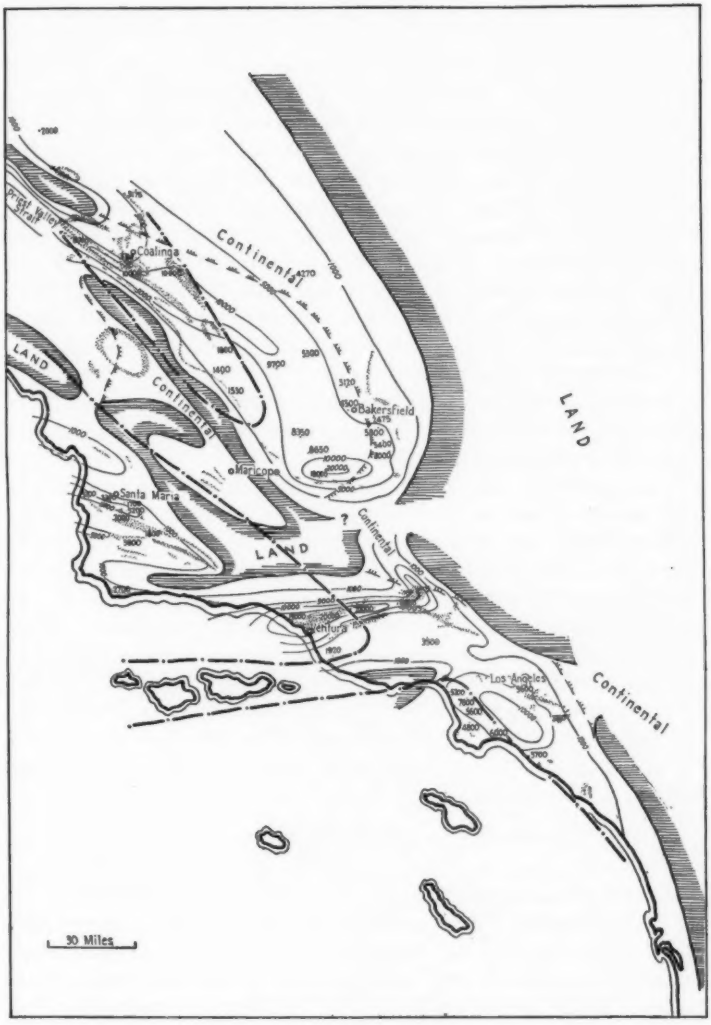


FIG. 22.—Pliocene-Lower Pleistocene paleogeography. Note the varying intervals of the isopachs.

During the Upper Miocene and probably not far from its midpoint there seems to have been a moderately intense disturbance in the San Rafael region. The cross-folding of the present Santa Ynez Mountains is thought to be a reflection of more intense folding in the area farther north. These cross folds are known to be post-Sespe, since the Sespe is involved in the folding east of San Marcos Pass; and they are cut by the Santa Ynez fault, which originated after the Miocene and probably after the Pliocene. That the folds originated during the middle Upper Miocene rather than in some other part of post-Sespe pre-Pleistocene time is inferred from the character and distribution of three masses of coarse intraformational breccia in the Upper Miocene Monterey shale of the Santa Barbara coast (Figs. 31 and 36). Each of these masses occurs near the plunging south end of one of the three most important cross folds; and two of the breccias are underlain by shale carrying middle Upper Miocene *Foraminifera*.

At the close of the Upper Miocene a marked decrease took place in the areas of most basins of deposition; in many localities, furthermore, the deposition of siliceous shale gave way to the deposition of argillaceous muds and coarser detrital materials. There is a change from marine to nonmarine conditions north of Coalinga, and an extensive overlap with unconformity in the Alcalde Hills. Southeast of Maricopa Upper Pliocene beds lie on Upper Miocene with an angular discordance of 30 degrees or more,[29] but the exact date of the folding or foldings is not evident. In the Piru district a discordance is found between Upper Miocene shale and a coarse-grained formation variously classed as Pliocene or uppermost Miocene. There is thus fair evidence for the hypothesis that an orogenic episode occurred at about the time commonly accepted as the end of the Miocene. The absence of marine Pliocene strata from many mountains with thick Upper Miocene marine strata adds to the evidence.

PLIOCENE AND LOWER PLEISTOCENE BASINS AND DEPOSITS

Figure 22 brings out the fact that Pliocene and Lower Pleistocene deposits of considerable thickness occur only in restricted parts of the old Miocene basins. In the main, they avoid the areas that were generally positive during the earlier Tertiary; or at most, they reach considerable thickness only in narrow basins like the Santa Maria Valley or Priest Valley strait.

The time from the end of the Miocene to the Middle Pleistocene orogeny was one of many transgressions and regressions and of several

[29] For an excellent photograph of this feature, see Plate 35-A in H. W. Hoots, "Geology and Oil Resources along the Southern Border of San Joaquin Valley, California," *U. S. Geol. Survey Bull. 812-D* (1930).

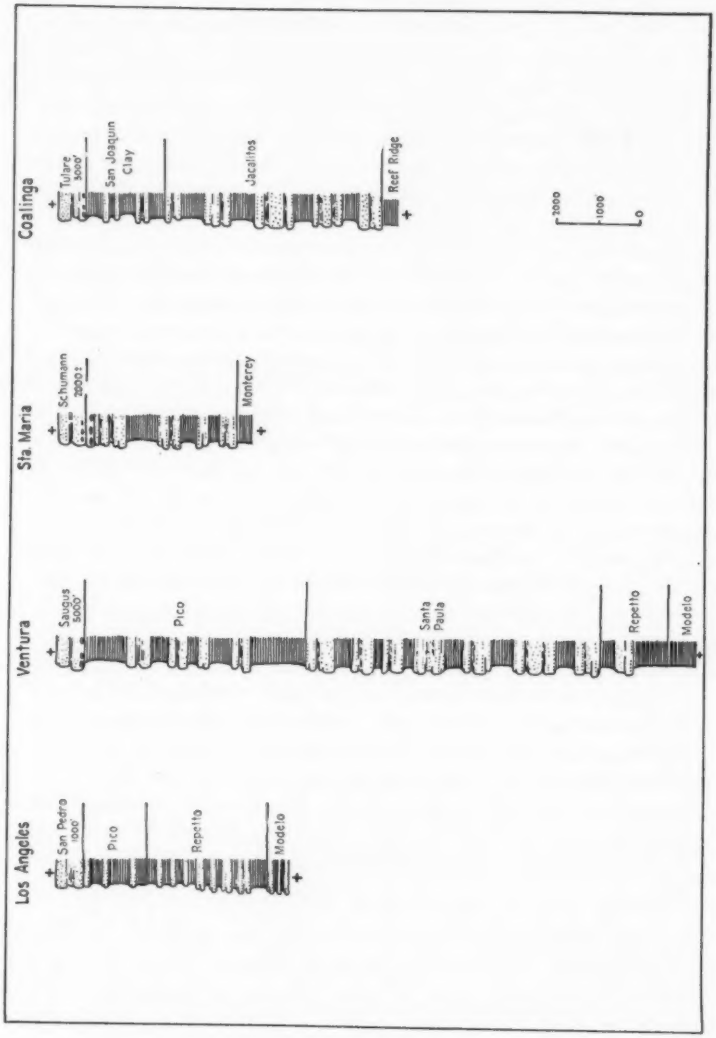


FIG. 23.—Pliocene columnar sections.

more or less local disturbances. In each of the major basins, accordingly, the deposits are divided into several formations and faunal zones. Because of the provincial nature of the faunas, however, it is not yet possible to correlate the deposits of the San Joaquin Valley with those of the Los Angeles or Ventura basin. For this reason it is not practical at present to discuss the evolution of the basins from stage to stage in as much detail as could be wished. In the present connection it will be sufficient, fortunately, to tell the story in general terms, leaving the necessary details to later sections that deal with some of the individual areas.

The three largest and most important masses of Pliocene deposits in Southern California are found in the Maricopa, Ventura, and Los Angeles basins. Thicknesses are very great: unknown, but probably 10,000–20,000 feet in the first; 18,000 feet in the second; probably 10,000 feet or more in the third. The Lower Pliocene deposits of the Ventura and Los Angeles basins are also remarkable in facies. Each of them carries foraminiferal assemblages many species of which are now living off the coast of Southern California at depths of one to two miles.[30] The Maricopa Basin Pliocene has not yet yielded evidence of similarly deep water during its accumulation. It is interesting, among other reasons, for the way in which it interfingers with nonmarine deposits, without marked change in thickness, along a curved line running from near Bakersfield to a point not far northeast of Coalinga. Alluvial and lacustrine deposits accumulated over the part of the Great Valley north of this line.

Lower Pleistocene deposits accumulated in all of the Pliocene basins but the sea remained only in those at the margins of the present ocean. The nonmarine Saugus, Paso Robles, and Tulare deposits date at least in part from this time. Thicknesses are of the order of 1,000–5,000 feet. The marine formations referred to the Lower Pleistocene include part or all of the Santa Barbara, the upper few thousand feet of folded beds in the Ventura Basin, and the Lomita, Timms Point, and San Pedro (Arnold's Lower San Pedro) of the Los Angeles Basin.

DISTURBANCES WITHIN PLIOCENE-LOWER PLEISTOCENE TIME

The best-authenticated discordant contact known within the Pliocene of California is perhaps the one at the base of beds containing a *Bulimina subacuminata* fauna, of Lower Pico age, in the beach section south of Eel River in Northern California.[31] Beneath it, with a dip

[30] M. L. Natland, "The Temperature and Depth-Distribution of Some Recent and Fossil Foraminifera in the Southern California Region," *Bull. Scripps Inst. Oceanography*, Tech. Ser., Vol. 3 (1933), pp. 225–30.

[31] D. D. Hughes, oral communication.

several degrees greater, is the *Bolivina angelina* subzone of the Repetto. The upper part of the Repetto, corresponding to 500 feet or more in the Los Angeles Basin, is cut out by erosion. That a similar unconformity exists in Southern California has long been suspected, but it has not yet been found.

A remarkable disconformity exists in the Repetto Hills between the Lower and Upper Pico. It is sufficiently general so that the Middle Pico *Bolivina robusta* beds do not outcrop anywhere east of the Newport-Inglewood belt, though they have been found in a great many wells, including some drilled in the basin at no great distance from its border. In the Ventura Basin no disconformity has been found at the corresponding horizon, but the occurrence of a contemporaneous regression is suggested by a marked coarsening of Middle Pico beds. In the San Joaquin Valley there is a similar widespread disconformity caused by a marine regression at about the horizon of the Upper *Mulinia* bed, but whether or not it corresponds in time to the *Bolivina robusta* regression is still uncertain. Unconformities of one kind or another have also been described in the Pliocene of the Santa Maria district, but nothing definite seems to be known as to how they correspond in time with those of other basins.

The end of the Pliocene, as now understood, was not a time of notable disturbance. In the San Joaquin Basin some slight oscillations of the bottom took place, but there as nearly everywhere else in the part of the State now emergent, the most striking feature was a general displacement of marine by fresh water. Only in a few places, such as the Los Angeles Basin and the perennially negative Ventura Basin, did the sea persist into the Lower Pleistocene.

Along the seaward margin of the Los Angeles Basin there is a remarkable angular unconformity between Lower San Pedro beds of Lower or Middle Pleistocene age and Upper San Pedro beds that are considered Upper Pleistocene.[32] In most other California localities where Pliocene beds are folded the conditions can all be satisfactorily explained on the assumption that the last strong folding of the Cenozoic was contemporaneous with this folding at San Pedro. Stille[33] has designated these movements at the Pasadenan orogeny.

With reference to the age of the oldest folded beds, it is interesting to notice that all of the supposedly cold faunas now known are found in them. The Upper San Pedro molluscan fauna contains some warm-

[32] H. S. Gale *et al.*, "Southern California," *XVI Int. Geol. Cong. Guidebook 15* (1933), pp. 8, 21, 34–43, *et cetera*.

[33] H. Stille, "Der derzeitige tektonische Zustand der Erde," translated as "Present Tectonic State of the Earth," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 20, No. 7 (July, 1936), pp. 849–80.

temperate forms that no longer live as far north as San Pedro, and has therefore been considered to be possibly interglacial. If so, the cool-water faunas contemporaneous with the later glacial stage or stages have not yet been discovered.

If the known cool-water faunas are Pliocene, as has often been suggested, we are in the curious position of knowing two cool-water faunas of the Upper Pliocene and none of the Pleistocene. If these faunas of the folded beds are Pleistocene, on the other hand, it is interesting to notice that approximately thirteen marine terraces[34] of post-folding age are found along the Southern California coast, and to reflect on the extreme difficulty of correlating any of them with definite stages of the Ice Age. In summary, the correlation of these deposits is so uncertain as to lead to many speculations but not to any very satisfactory conclusions.

POST-PLEISTOCENE (POST-UPPER SAN PEDRO) DISTURBANCES

That faulting has gone on in California since the Pleistocene and that it still continues are well-established facts. It is thus not surprising to learn that the Upper San Pedro and correlative formations have been faulted and steeply tilted, and even arched into definite anticlines in some of the more active areas. That most Coast Range anticlines have been posthumously uplifted in post-Pasadenan time is, as a matter of fact, also well established. So general is this condition that only a small proportion of the known folds of the State totally lack topographic expression. Typical examples of the normal conditions are furnished by Kettleman Hills and Elk Hills in the San Joaquin Valley or Signal Hill and Ventura anticline in coastal California.[35]

Conclusion on Diastrophic History

From this review of Coast Range diastrophic history, it is clear that diastrophism has progressed spasmodically. Some short periods have been typically orogenic, some longer ones typically epeirogenic. It is also clear, wherever correlation data are adequate, that all tectonically comparable areas have been similarly affected during each orogenic or non-orogenic period. So far as the available data permit us to judge, therefore, California structural history has involved an alternation of widespread orogenic and epeirogenic phases.

It must be admitted, however, that so far as one can see at present there have been periods that were not definitely either orogenic

[34] *Cf.* W. P. Woodring, "Fossils from the Marine Pleistocene Terraces of the San Pedro Hills, California," *Amer. Jour. Sci.*, Vol. 29 (1935), pp. 292–305.

[35] A discussion of the meaning of these recent disturbances and their importance for tectonic geology may be found in the paper by Stille, already cited.

or epeirogenic. In some cases, like the post-Lower Miocene disturbances or like the present with its faulting, the trouble may perhaps be taken care of by revised definitions. In other cases the solution may involve the admission that epeirogenic movements, at their maximum, may produce results closely similar to those produced by weak orogenic disturbances.

Perhaps the most surprising suggestion brought out by this study is the one concerning the short-lived character of some disturbances. As noted earlier, the "Temblor" fauna ranges above and below the sharp unconformity marking the post-Lower Miocene disturbance; the beds above and below the post-Middle Miocene unconformity have generally been thrown together as "Monterey" or "Modelo"; and the time represented by the last great orogeny, that of the Middle Pleistocene, was too short to permit any specific change in such rapidly changing animals as horses and elephants. If the apparent meaning of this fact is grasped, it will be evident that even if we should find twice as many orogenies in the Tertiary as we now suspect, we shall not be justified from this fact alone in believing that orogeny is a continuous phenomenon. If the Miocene was 15 million years long, and if it included three orogenic disturbances lasting altogether a half million years, then the times of epeirogenic calm would have amounted to 30 times the length of the disturbed periods. At present there is no evidence that the disproportion may not have been even greater; that is, that the epeirogenic part of the Miocene may not have been more than 30 times as long as the three known disturbances taken together.

CHAPTER III

NORTHERN GEOSYNCLINAL BASIN AND COALINGA DISTRICT

An attempt has been made in the foregoing pages to show that the diastrophic history of Southern California is closely related to the structural pattern illustrated in Figures 2 and 6. The following pages describe in greater detail the several provinces—three negative areas separated by two dependencies of the major positive area to the east—that constitute the elements of this pattern, and show how some of the more important structural details such as faults, folds and basins are related to them.

Northern Geosyncline

The Northern Franciscan area is bounded on the east by the San Joaquin Valley subprovince of Mohavia and on the west by Salinia. It extends hundreds of miles northward beyond the bounds of Southern California, but shows throughout its extent many of the features that characterize the part within our boundaries. Its most striking feature, to which apparently many of its other peculiarities are related, is the possession of a basement of Franciscan rocks. These rocks are commonly supposed to lie upon granite, and may do so. If the granite is everywhere present under the Franciscan, it is presumably either intrusive into it, or unconformable beneath it. The writers see no available method of deciding at the moment whether the granite is present, or if so, whether it is intrusive or unconformable.

The eastern boundary of the Franciscan is also uncertain. A well drilled south of Merced, not far from the center of the Valley, passed from Upper Cretaceous rocks directly into granite. Partly for this reason, and partly because the strong folds and faults of the Coast Ranges meet the very slightly folded and faulted strata of the San Joaquin Valley along a nearly straight line, it is generally assumed that the Franciscan rocks are either absent or very poorly represented under the Valley. The boundary as drawn on the writers' maps is located on this supposition.

In passing, it is worth noting that some beds showing many resemblances in lithology to the Franciscan occur west of the Mother Lode in the foothills of the central Sierra Nevada. The stratigraphy and structure of these rocks are not well known at present, and the occurrence is in any case beyond the limits of Southern California, as here defined.

The western boundary of the Northern Geosyncline is sharp and precisely drawn, being the San Andreas fault. A discussion of the origin and nature of this well-known structural feature will be found on a later page of this chapter.

So far as can be seen at present, the Northern Franciscan basin remained substantially a unit during the Mesozoic, but became divided into subprovinces about the beginning of the Tertiary. The subprovinces south of Coalinga are here called the Diablo uplift, and the San Joaquin embayment. The Diablo uplift was generally positive during the Tertiary, being raised during each regression, though partly flooded during the greater transgressions. The San Joaquin embayment was generally negative and has therefore a much more nearly complete section. At its boundary with the uplift there is a magnificent series of overlaps and unconformities that have fascinated California geologists for a generation or more.

Perhaps the best way to furnish a satisfactory idea of the chief features of this Northern basin will be to describe briefly the general geology of the region south and west of Coalinga, as far as Devils Den and Lost Hills. The chief features of this interesting district are described and illustrated in several publications of the United States Geological Survey,[38] and some of them have been discussed in shorter publications. The writers' summary draws on all published and many unpublished works, and also upon observations made by one or both of the writers.

GEOLOGY OF THE COALINGA DISTRICT

The geography of the Coalinga district is illustrated in the sketch map, Figure 24. The town of Coalinga lies in a sub-circular valley plain, Pleasant Valley, which is continued northwestward, greatly narrowed, in White Creek and Los Gatos Creek valleys. To the south and southeast it merges with the synclinal Kettleman Plain, which persists as far as the south border of the district. North of Pleasant Valley rises a 4,000-foot anticlinal mountain, Joaquin Ridge, which is continued to the southeast, by the much lower Anticline Ridge, the site of the Eastside oil field. The southward continuation of this ridge, and the east border of the Kettleman Plain, is formed by the Kettleman Hills. Three low passes connect the Pleasant Valley-Kettleman Plain lowland with the main San Joaquin Valley plain. Two of these passes coincide with structural saddles, one of them lying be-

[38] See especially R. Arnold and R. V. Anderson, "Geology and Oil Resources of the Coalinga District," *U. S. Geol. Survey Bull. 398* (1910).

R. W. Pack and W. A. English, "Geology and Oil Prospects in Waltham, Priest, Bitterwater, and Peachtree Valleys," *ibid., Bull. 581-D* (1914).

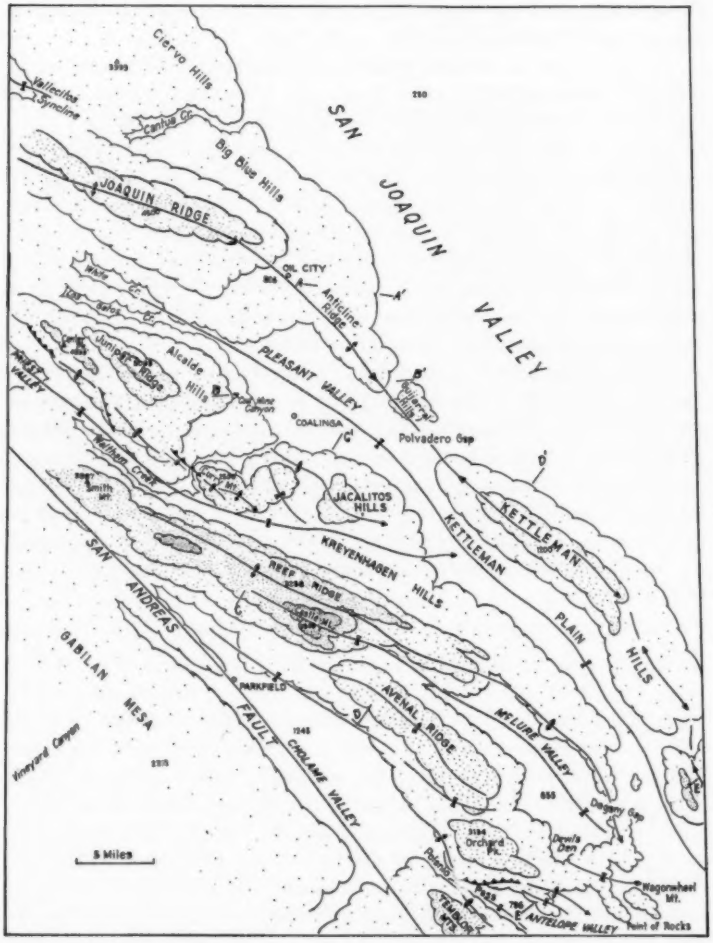


FIG. 24.—Map of Coalinga district. Topography suggested by lines that approximate contours and by stippling. There is no definite contour interval. Fold axes and some faults are also shown.

PLATE III-A.—Curry Mountain from the south. The top of the ridge is Cretaceous, the flanks are Pliocene. Jacalitos Creek is in middle distance.

PLATE III-B.—Looking north up Sespe Creek at the type locality of the Sespe "brownstone."

tween Anticline Ridge and the North Dome of Kettleman Hills, the other between the Middle and South domes.

West of Pleasant Valley rises a tilted plateau-like area, the Alcalde Hills, culminating toward the west in Juniper Ridge and the other rough, mountainous ridges north of Waltham Valley. Curry Mountain and the Jacalitos Hills belong structurally with the Alcalde Hills-Juniper Ridge country, but are separated from it by the deep Alcalde Canyon of Waltham Creek. Southeast of Jacalitos Creek stretches the belt of canyon-crossed ridges known as the Kreyenhagen Hills. Toward the southwest these hills rise toward the narrow, saw-toothed Reef Ridge, with Castle Mountain lying in the background a mile or two farther southwest. Castle Mountain itself is a great open syncline, and is continued toward the southeast by the much lower synclinal McLure Valley.

McLure Valley is separated from the Kreyenhagen Hills and Kettleman Plain by an interesting ridge composed of anticlinally folded Upper Miocene siliceous shale, the McLure shale. Toward the south the valley is bounded by the complex group of low hills near Devils Den, and to the southwest by the anticlinal mountain, Avenal Ridge, and by Orchard Peak.

Stratigraphically, the Coalinga district is characterized by a nearly complete series of Mesozoic and Cenozoic formations, most of which are subject to much lateral variation (Fig. 25). The most nearly continuous sections lie to the east and northeast; the most discontinuous to the west and southwest. The intermediate belt, corresponding to the foothills west of Pleasant Valley and Kettleman Plain, is characterized by numerous overlaps and unconformities.

MESOZOIC FORMATIONS

Franciscan and granite.—Lower Mesozoic Franciscan rocks crop out over considerable areas near the San Andreas fault. Farther northeast they are commonly found only in elongated, generally narrow belts that form the cores of some of the major anticlines. That they underlie the entire district, from the San Andreas fault to the west edge of the San Joaquin Valley and perhaps farther, is a reasonable assumption for which, however, direct evidence is still lacking.

The Franciscan complex of this district includes igneous, sedimentary, and metamorphic rocks of all the kinds commonly found associated in other Franciscan areas. The harder rocks are commonly broken and veined, the softer ones crushed and slickensided. The "blue band," which for a distance of several miles forms a narrow core along the axis of the Reef Ridge anticline, contains small frag-

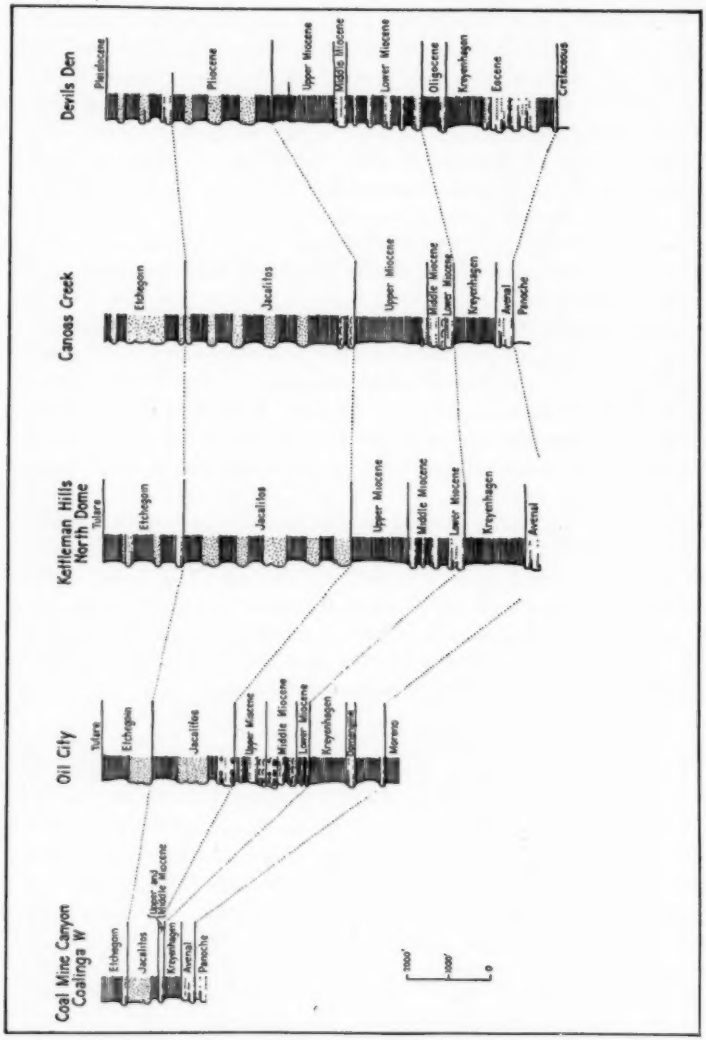


FIG. 25.—Columnar sections of the Tertiary of the Coalinga district.

ments of sandstone, basalt, serpentine, radiolarian chert, glaucophane schist, and many others, all thoroughly kneaded together. Many other occurrences are similar, but some are less heterogeneous.

Structurally, the Franciscan complex is like a mass of dough with a minor proportion of hard constituents interspersed. Except when it is overlain by a thick series of highly resistant beds, its instability permits the superjacent formations to become broken and bent very irregularly. Many large and small folds of the Coalinga district are of the diapir type, as has been noted by many students of the district. They are thus similar to Mount Diablo[37] and other "upthrust" areas farther north.

Cretaceous.—The Cretaceous rocks of the Coalinga district include *Aucella*-bearing dark shale, sandstone, and conglomerate, some of which may prove to be Upper Jurassic; thick Upper Cretaceous conglomerate, sandstone, and shale; and locally, 1,000–2,000 feet of brownish or purplish siliceous and calcareous, diatomaceous, and foraminiferal shale. The last-mentioned member is not certainly recognized in outcrop south of Coalinga, but presumably underlies the outer foothill belt.

In the area nearest the San Andreas fault, the Cretaceous is preserved only as larger or smaller patches of *Aucella*-bearing shale. On the slopes of the higher ridges there are larger masses of great thickness, the Upper Cretaceous members of the series being well represented. Toward the east they are irregularly overlapped by different Tertiary formations, almost any one of which may locally lie upon the Cretaceous or even upon the Franciscan. The total thickness of strata referred to the Cretaceous amounts to 25,000 feet or more, but in many sections there is only 5,000–10,000 feet exposed between the underlying Franciscan and overlying Tertiary formations. The thinning is due in part to erosion in most cases, but in some it seems to be due largely to irregular subsidence during the time of Cretaceous deposition. On Joaquin Ridge, for example, the Cretaceous is much less than half as thick as it is in Alcalde Hills to the southwest, or in Panoche Hills to the north, and the difference seems to be due not to erosion during or after the Cretaceous, but simply to a slower subsidence of this area. So far as the Upper Cretaceous is concerned, at any rate, there seems to be no absence of any member, but instead a marked thinning of each of them. Additional study of this important feature and of many other features of the Cretaceous of this district is greatly needed, and is long overdue.

[37] J. A. Taff, "Geology of Mount Diablo and Vicinity," *Bull. Geol. Soc. America*, Vol. 46 (1935), pp. 1079–1100.

CENOZOIC FORMATIONS

As already suggested, the Cenozoic formations are distributed in three belts; a belt of remnants in the higher ridges and intervening synclinal valleys; a belt in which most formations are present but each one likely to be in unconformable relation with any other, in the higher foothills; and a belt of thick, nearly continuous formations under Kettleman Plain and the Kettleman Hills. The formations are referred to the Eocene, Oligocene, Miocene, Pliocene, and Pleistocene epochs.

Eocene.—True Martinez beds are definitely known only north of Joaquin Ridge, but they probably underlie the outer foothill belt farther south. The "Martinez (?) formation" of Anderson and Pack is now generally considered to be Lower and Middle Eocene. The beds of Eocene age include the Cantua, Avenal, and Domengine sandstone members, a thick clay shale member north of Coalinga and a thinner one in the Devils Den area, and a white siliceous shale member in each area of Eocene outcrops. In its content of siliceous shale and coal members, the Coalinga Eccene resembles that of the central part of California and differs from that in most areas farther south.

In the vicinity of Big Tar Canyon and the southeast end of Reef Ridge, the basal member of the Eocene, the Avenal sandstone, lies with an angular discordance of about 30 degrees upon pre-Moreno Cretaceous. Elsewhere, as on the Coalinga anticline and at Devils Den, the Cretaceous-Eocene contact seems to be merely disconformable. The general absence of Paleocene strata and the local occurrence of an angular discordance are among the reasons for believing that the Diablo uplift came into existence at the beginning of the Tertiary.

Oligocene.—For many years the several occurrences of Kreyenhagen shale were grouped together as doubtfully Oligocene in age. Foraminiferal studies of the last few years have shown that the Kreyenhagen is a composite formation, however, and that only the upper part in a few areas seems referable to the Oligocene.[38] It carries a small molluscan assemblage and the *Uvigerina "glabrans"* foraminiferal faunule. In most exposures it is cut out by the unconformity at the base of the overlying Miocene. The basal part is commonly a sandstone, in many places glauconitic.

The Oligocene strata in this district constitute merely a minor part of the easily deformable Kreyenhagen shale. They are very diferent lithologically from the more southerly occurrences of the Oligocene.

[38] E. R. Atwill, "The Oligocene Tumey Formation of California," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 19 (1935), p. 1192.

Miocene.—The Miocene formations of the district include a transgressive Lower Miocene series of shale and sandstone; a more transgressive Middle Miocene series of similar character; and a locally transgressive Upper Miocene formation which is dominantly white sandstone north of Coalinga, and brown, often white-weathering, siliceous shale south of Coalinga. The Lower and Middle Miocene series include the Temblor and Big Blue members.

The Wagonwheel Mountain section near Devils Den has representatives of Lower, Middle, and Upper Miocene separated by unconformities. The Temblor formation of Reef Ridge includes Lower and Middle Miocene representatives near the southeast end of the ridge, but only Middle Miocene, resting upon Eocene or Cretaceous, farther northwest. In Alcalde Hills the Miocene strata are so thin and poorly exposed that doubt has long existed as to the correlation of the beds found there. The entire thickness is only a few feet, and fossils collected from different beds have been referred to Middle and Upper Miocene.

North of Coalinga the Temblor formation includes leaf-bearing beds (Lower Miocene?) at the base, a calcareous reef bed near the middle, and the Big Blue member with its serpentine detritus at the top. The Big Blue has an eroded and mollusk-bored upper surface and is overlain by the sandy shale and white littoral sandstone of the Santa Margarita. The age and origin of the Big Blue give rise to interesting problems that will be discussed in a subsequent passage.

The most continuous Miocene section in the district has been revealed by the deep wells of Kettleman Hills. If the Reef Ridge formation of disputed age is omitted, the Miocene strata are here 3,000–4,000 feet thick, with Upper, Middle, and Lower series well represented. Some details will be given in connection with the problem of the origin and age of the Big Blue.

In the mountainous district southwest of Reef Ridge, Middle Miocene reef beds and Upper Miocene McLure shale commonly occur together. In the McLure Valley syncline, however, the McLure shale rests upon the Cretaceous nearly everywhere except at the south end, where Middle Miocene sandstone is found.

The age and origin of the Big Blue.—The Big Blue was probably named by early drillers or still earlier settlers in the Coalinga district. It was discussed at some length by Arnold and Anderson,[39] who mention it as a "zone of bluish-gray and variegated clay, sand, gravel, and serpentine detritus locally known as the Big Blue." Finding it

[39] "Geology and Oil Resources of the Coalinga District, California," *U. S. Geol. Survey Bull. 398*, p. 76 ff.

between fossiliferous "Vaqueros" and Santa Margarita formations, they referred it to the Upper Miocene, supposing that an important unconformity, not visible where they studied the contact, might exist at its base. They described its use as a marker in the Coalinga Eastside wells, and noted that its texture becomes coarser northward from the field. They pointed out that the member must have been formed by streams draining from a nearby area of Franciscan rocks like that now exposed on Joaquin Ridge.

In extending northward the geologic mapping begun in the Coalinga district, Robert Anderson and R. W. Pack had the opportunity to study the member in the Big Blue Hills where it has its maximum thickness and most striking characteristics. They reported that

> it is remarkable for being little else than a compacted mass of serpentine dust, flakes, and pebbles. With this shale are conglomerates formed almost entirely of serpentine bowlders, the largest of which are huge blocks many feet in diameter.

A photograph shows a boulder so large that it completely dwarfs a horse standing beside it. They noted the variable thickness, from 40 to about 1,000 feet. The areal extent of outcrop of the member is given as about 20 miles, from the Eastside field to a point northeast of Ciervo Mountain.

On the origin of the Big Blue, Anderson and Pack wrote:[40]

> The sedimentary nature of the beds is unquestioned . . . and the material forming them must have been weathered and transported from a near-by landmass of serpentine, which was almost certainly that on the summit of the range [Joaquin Ridge] south of New Idria. An inspection of the geologic map will show the relatively small extent of the Big Blue and its close geographic relation to the serpentine at the crest of the range.

The geographic relation mentioned in this passage is striking, but it should be noted that no Big Blue outcrop is nearer the serpentine mass than six miles.

On the age of the member, Anderson and Pack were forced to disagree with earlier views because of the discovery of "Vaqueros" fossils "at several points in the Ciervo and Big Blue hills in sandy beds interstratified with or overlying the serpentinous beds of the Big Blue. . . . " Later workers have confirmed this discovery, though the fossils called Vaqueros by Anderson and Pack are now called Temblor and are referred to the Middle Miocene. This conclusion is in harmony with the views of vertebrate paleontologists, as summarized recently by Bode.[41]

[40] "Geology and Oil Resources of the West Border of the San Joaquin Valley North of Coalinga," *U. S. Geol. Survey Bull. 603* (1915), p. 84.

[41] Francis D. Bode, "The Fauna of the Merychippus Zone, North Coalinga District, California," *Carnegie Inst. Washington Pub. 453* (1935), p. 85.

The oil wells of the Kettleman Hills have unexpectedly thrown new light on the question of the age of the Big Blue. As suggested in Figure 26, it seems to be represented in this field by a shaly member called the "Upper Variegated," which lies about 300 feet below the base of the siliceous Upper Miocene McLure shale. It lies upon coarse sand about 125 feet thick, which lies in turn upon 100 feet of black shale referred by Goudkoff and many other paleontologists to the lower Middle Miocene "Gould shale." In summary, the Upper Variegated shale in this area lies near the middle of that part of the Kettleman sand which most workers take to represent the Middle Miocene. The suggestion is obvious, though not demonstrable at present, that the Upper Variegated shale and the Big Blue should be attributed to a diastrophic disturbance that took place about the middle of the Middle Miocene; that is, between *Baggina robusta* and *Valvulineria californica* time. If this surmise is correct, it seems likely that a *Valvulineria californica* fauna may eventually be found either in the Upper Variegated shale itself or in the sandstone overlying it.

At first sight it would seem simpler to assume that the Big Blue resulted from local uplifts either at the beginning or end of Middle Miocene, since widespread disturbances in coastal California are known to have occurred at both these times. So far as the Coalinga district is concerned, it should be noted that neither of these disturbances seems to have strongly affected the Franciscan areas. The pre-Middle Miocene disturbance was closely followed by a widespread transgression over much of the exposed Franciscan, and the later disturbance was immediately followed by the deposition in the same areas of Upper Miocene beds of two types: white granitic sand, and siliceous shale. Neither type of lithology suggests that strongly uplifted areas existed at this time in the Franciscan belt. The evidence from physical geology is thus in harmony with that from paleontology and stratigraphy in suggesting that the Big Blue belongs to the middle rather than to the beginning or end of the Middle Miocene, even though this conclusion makes it necessary to introduce into the writers' list a new period of locally strong diastrophism.

Pliocene.—The dividing line between Miocene and Pliocene in this district has long been in dispute. It is now generally agreed that the McLure shale is Miocene and the Jacalitos-Etchegoin series Pliocene, but the correlation of the intervening Reef Ridge shale is still in doubt. Barbat and Johnson refer it to "uppermost Miocene on the basis of the stratigraphic relations and faunal content."[42] Goudkoff reports, on the other hand, that

[42] W. F. Barbat and Floyd L. Johnson, "Stratigraphy and Foraminifera of the Reef Ridge Shale, Upper Miocene, California," *Jour. Paleon.*, Vol. 8 (1934), p. 11.

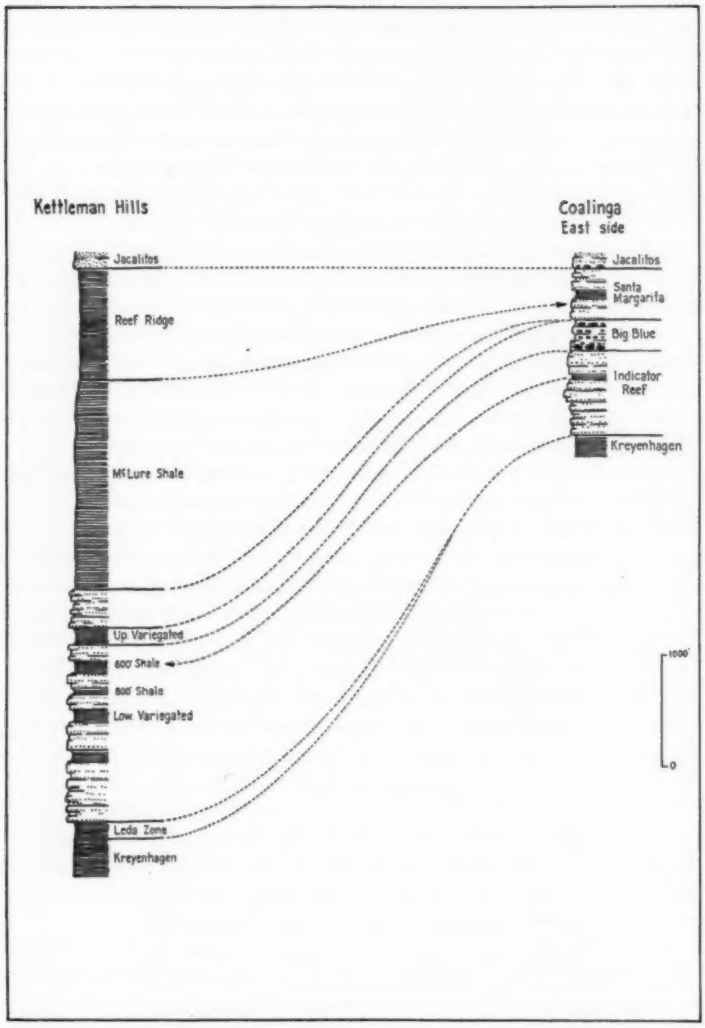


FIG. 26.—Columnar sections to show the position of the Big Blue in Miocene of Eastside field, and its correlation with the "Upper Variegated" shale of Kettleman Hills wells.

the microfauna in the upper part of the so-called "caving blue shale" or Reef Ridge formation shows that this part is much more closely related to the overlying Jacalitos than to the lower part of the "caving blue shale."[43]

It would seem, therefore, that the lower part, at least, of the formation is Upper Miocene, as the limit is now drawn in California, but the age of the upper part is not agreed upon by all interested parties. If the Reef Ridge south of Coalinga is shown to be the equivalent of the Santa Margarita north of Coalinga, as many geologists consider likely, the case for a Miocene age of the former will be greatly strengthened —unless Coast Range geologists decide to follow the lead of those vertebrate paleontologists who call the continental correlatives of the Santa Margarita, Lower Pliocene.

The undoubted Pliocene strata consist of the Jacalitos and Etchegoin formations of Arnold and Anderson—referred by them to the Upper Miocene—the "Etchegoin group" of Nomland, the Etchegoin and overlying San Joaquin clay of Barbat. The word "Etchegoin" is thus used for the whole series, for the upper part only, and for the lower part, by three of the most influential writers on Coalinga stratigraphy. For present purposes the question of nomenclature is fortunately not important. The strata are nearly all marine south of Coalinga, though a few nonmarine or brackish-water intercalations occur in the upper third of the series. They consist of hard or soft, gray, brown or blue sandstone members interbedded with sandy or clayey soft shale. Several of the fossil beds may be traced in outcrop for many miles. In some places the shales yield *Foraminifera*, mostly of shallow-water type such as *Elphidium*.

North of Coalinga the marine members thin out and the entire section becomes nonmarine within a distance of a few miles. This change takes place across an eastward trending belt, the south edge of which runs across the Eastside oil field. It is an interesting fact that a striking change in facies of both Upper Miocene and Pliocene formations takes place in this same area.

The Coalinga area is thus seen to have formed the northern margin of the Pliocene San Joaquin Valley sea. It was connected with the ocean through a strait across what is now Priest Valley. The sandstone members of the Pliocene are thicker and more prominent along this old strait and immediately in front of it to the southeast than elsewhere. Toward the south and southeast the sandstones are finer-grained, the shales more commonly clayey or even diatomaceous. The nonmarine intercalations in the upper part of the series are so persist-

[43] Paul P. Goudkoff, "Subsurface Stratigraphy of Kettleman Hills Oil Field, California," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 18, No. 4 (April, 1934), p. 473.

ent that they have been recognized in deep wells throughout most of the southern San Joaquin Valley.

Perhaps the best evidence for considering these beds Pliocene comes from the occasional mammalian fossils that have been collected from them. Thus, the basal Jacalitos has yielded a *Neohipparion* near *molle;* the middle beds carry *Pliohippus coalingensis*, the upper ones *Plesippus* (or *Equus*) *proversus*.

Pleistocene.—At the end of Etchegoin time the sea withdrew finally from the Coalinga district and a small amount of warping, with local erosion, took place. Subsidence continued thereafter until 2,000–3,000 feet of the nonmarine Tulare formation had accumulated. During this subsidence the Coalinga foothill belt west of Kettleman Plain seems to have lain near the edge of a lake that covered much or all of the San Joaquin Valley. As it is exposed in the Kreyenhagen Hills the Tulare formation carries huge lenses of conglomerate that may mark the mouths of streams that drained into the lake from the rising mountain area to the west. The conglomerates carry fragments of Cretaceous and Tertiary formations, including boulders of the Temblor reef beds and cherts from the McLure shale.

The Tulare formation is separated by a profound angular discordance from the arched and tilted deposits dating from the later Pleistocene. A period of strong folding and vigorous erosion must therefore have taken place during a part of the Pleistocene. It was followed by deposition in some of the lower areas and by renewed arching and minor faulting in local areas.

On the date of the stronger folding here referred to the Middle Pleistocene, it may be noted that W. F. Barbat has suggested a chronology that would make the Tulare formation fairly late Pleistocene. He suggests, in brief, that most of the San Joaquin clay formation of the series here called Pliocene should be considered Pleistocene.[44] Other paleontologists have suspected, on the other hand, that at least the lower, fossil-bearing part of the Tulare formation should be referred to the Pliocene. Students of the fossil vertebrates, a few of which have been found in or near the base of the Tulare, incline to the view here followed, namely, that the base of the Tulare lies approximately at the Pliocene-Pleistocene contact.

The structural evolution of the Coalinga district is related to that of the major province, the Northern basin, of which it forms a part. This province became differentiated about the end of the Cretaceous into a positive area lying toward the west, and a negative

[44] W. F. Barbat and John Galloway, "San Joaquin Clay, California," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 18, No. 4 (April, 1934), p. 495.

area lying between this positive area and the western edge of Mohavia. The positive area is the Diablo uplift of Figure 6; the negative area is the San Joaquin embayment. The Coalinga district of the present discussion contains parts of each.

An attempt to discuss the structural evolution of the district meets at the outset the difficulty that the distribution and thickness of the different members of the Knoxville-Chico strata are very inaccurately known. The early workers were unable to study the series adequately because it showed little prospect of yielding commercial oil fields; later workers have faced the same handicap to an even greater degree.

From the available data it seems safe to conclude that the most active areas of Cretaceous subsidence shifted from time to time and that the rate of subsidence, along with the rate of accumulation of sediments, differed much in different areas. Thus the Lower Cretaceous underlies Priest Valley and Juniper Ridge, is absent from Joaquin Ridge, but has been recognized[45] in the Panoche Hills farther north. Similarly, the Upper Cretaceous beds are more than 20,000 feet thick west of Coalinga, thin to half of that amount or less on Joaquin Ridge, and thicken to 25,000 feet in Panoche Hills. These facts suggest strongly that Joaquin Ridge was represented during the Cretaceous by a belt of marked thinning transverse to the axis of the old Northern Geosyncline. A study of the best geologic data available indicates that during at least the Upper Cretaceous the area of the present ridge was continuously submerged, but the different sedimentary members are much thinner than their analogues farther north and south. The absence of the Lower Cretaceous may mean either nondeposition, or removal by erosion during a (hypothetical) post-Knoxville erosion interval. In any event, Joaquin Ridge seems to have been represented by a *Schwelle* during the Upper Cretaceous. The positive character that it acquired not later than the end of the Lower Cretaceous seems to have persisted during the Cenozoic, and, as already indicated, to have been especially pronounced at certain times, as during the middle of the Middle Miocene.

Owing to lack of detailed study of the Cretaceous farther south, there is room for much diversity of opinion as to the Cretaceous structural conditions there, but there are several suggestions that some, at least, of the great Cretaceous anticlines were also represented by areas of thinning and perhaps of recurrent folding in pre-Cenozoic time.

In any case, there is strong evidence that the Coalinga district was folded very early along east-west lines, and that these early folds

[45] J. A. Taff, oral communication.

were later interrupted and cross-folded along lines more nearly parallel to the long axis of the old geosynclinal basin. An analysis of the Coalinga-Kettleman Hills-Lost Hills line of folds, represented in Plate I as a continuous fold, will illustrate the complexity of structural history in the district.

At Oil City the Moreno shale member of the Cretaceous is present on the axis of the fold. It is overlain disconformably by "Meganos" shale, probably lower Middle Eocene in age. Above the "Meganos," disconformably and with a slight discordance, comes the Domengine sandstone, upper Middle Eocene, which is overlain, also disconformably, by the Upper Eocene Kreyenhagen. The Tumey formation (Oligocene) is absent, though it occurs farther north in the Ciervo Hills, and at great depth to the south in the Kettleman Hills. Both Lower and Middle Miocene strata are probably present on the axis of the anticline near Oil City, but are overlapped by Upper Miocene and Lower Pliocene a short distance to the southwest. Both Upper Miocene and Lower Pliocene are at least disconformable, even where the section is least interrupted.

In summary, the whole Tertiary section is discontinuous in this area. Strongly regressive members are absent, disconformities and small angular discordances occur in the formations of all epochs.

In the Kettleman Hills, conditions are accurately known only to the Middle Eocene, probably Domengine. Every member of the later Tertiary that is known anywhere seems to be represented, and there is at present no proof satisfactory to everybody that any member is thinner along the axis of the anticline than it is in adjacent areas east and west. The Reef Ridge formation has been thought to be considerably thinner by some workers, but others attribute this appearance to an erroneous choosing of upper or lower contact. In any event, even if the fold was forecast by a mild thinning of certain post-Miocene members, the amount of this thinning was so slight as to be within the limits of the measurements available at present. We seem justified in asserting that if a geologist could have examined the Kettleman Hills area during the Lower Pleistocene, and could have secured an accurate three-dimensional picture, he would probably not have suspected that any Kettleman Hills anticline was about to be born. Instead he would probably have guessed that future diastrophism would continue to develop the cross-folds that had been recurrently or perhaps continuously growing ever since some time in the Cretaceous.

At the end of the Pliocene the sea-connection across Priest Valley was finally broken, and the fresh-water conditions of the northern

San Joaquin Valley spread south to the San Emigdio region. Subsidence continued, however, until a few thousand feet of nonmarine Lower Pleistocene strata had accumulated over the site of the earlier marine embayment. The mid-Pleistocene orogeny then began. It re-elevated earlier anticlines and probably broke some broad, simple folds into two or more small, sharply compressed folds. Many folds were badly faulted along one or both sides. If any old faults existed—a highly uncertain matter—they may have become rejuvenated. The Joaquin Ridge anticline, which had been in existence as far east at least as the Oil City region, grew southeastwards at an amazing rate. In the Lost Hills region, its new prolongation may have crossed another old line of cross-folding, the Devils Den line. If this analysis of the structural evolution of the region is correct, the Kettleman Hills fold is a youthful appendage to an ancient, perhaps a Mesozoic, fold.

The Pyramid Hills anticline bears a similar relation to the Reef Ridge-Castle Mountain fold, which has along its axis the narrow serpentine "blue band." The Pyramid Hills fold is narrow and steep-sided, and connects the broad Cretaceous fold to the northwest with the complex cross-fold of Devils Den. In this case, also, it is likely that the Cretaceous fold was formed early, since a discordance of 30 degrees or more is found between Upper Cretaceous and Middle or Lower Eocene along its northeast flank.

The faults of the Coalinga district, though numerous and interesting, are commonly small. A great many exist in the axial part of the Kettleman Hills folds, and seem to be due[46] to the stretching of the upper members in a thick series of beds that were arched to form a huge anticline. The faults bounding the serpentine mass on Joaquin Ridge are presumably related to the upward squeezing of the serpentine mass during several folding periods, beginning perhaps with that of the Middle Miocene. The Los Gatos Creek fault zone consists of numerous minor fractures in a massive sandstone series that has been bent into a sharp syncline since Upper Pliocene time. The Jacalitos fault is scarcely more than a zone of vertical beds along the flank of a strongly asymmetrical anticlinal fold. It occurs in an area of strong thinning of the Pliocene, as shown by wells drilled southwest and northeast of it. Further compression would probably change it into a low-angle thrust fault with a dip of the fault-plane toward the side with the thicker section (southwest). It may thus be thought of as an embryonic representative of such faults as the Santa Ynez and Big Pine faults.

[46] Mason L. Hill, "Origin of Faulting in the Kettleman Hills, California," *Proc. Geol. Soc. America for 1934* (1935), p. 322.

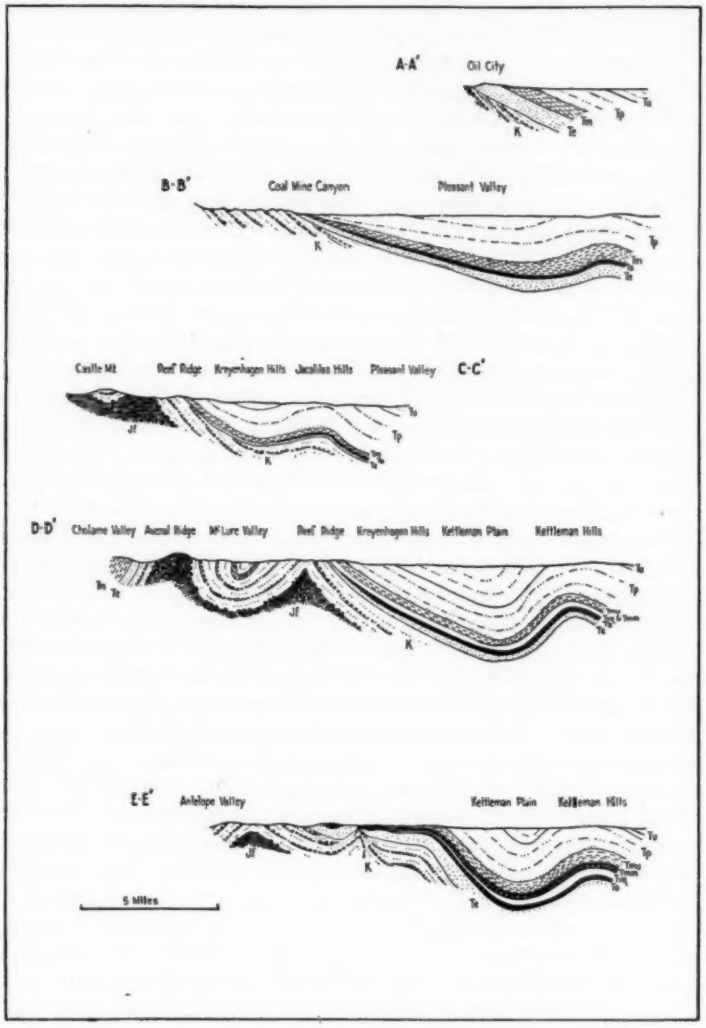


FIG. 27.—Structure sections in Coalinga district. *Jf*, is Franciscan; *Te*, Eocene; *To*, Oligocene; *Tu*, undifferentiated Miocene; *Tvq*, Lower Miocene; *Tmm*, Middle Miocene; *Tmu*, Upper Miocene; *Tp*, Pliocene; *Tu*, Tulare (Lower Pleistocene). Lines of sections are shown in Figure 24.

The Waltham Canyon fault zone is developed[47] along the steep flank of an asymmetrical anticline, and is complicated by the fact that its axis lies near the thin edge of a great wedge of beveled Cretaceous strata lying chiefly to the northeast, and a Franciscan mass lying to the southwest (Plate I).

The Castle Mountain fault zone is axial to a compressed anticlinal fold in the Cretaceous. Toward the southeast where this fault zone meets the southeast end of Reef Ridge, poor exposures make a determination of the actual conditions difficult and leave the field to a series of competitive and for the most part highly imaginative theories in which old faults play a great role. All of the observed conditions are consistent with the hypothesis that the fault dies out before reaching this area, and that the pre-Upper Miocene diastrophism consisted entirely of folding.

In the higher mountains there are many faults, most of them thrusts along the flanks of steep, asymmetrical anticlines. Along many of them masses of Franciscan serpentine have welled up, like the salt cores in certain anticlines in other regions. Several faults of this type are shown in Plate I, and more adequately in such maps and structure sections as those of Pack and English.[48]

The age of most of the faults in this district is undoubtedly Pleistocene. Some of those found in the higher mountains are possibly, perhaps probably, older; perhaps as old as the Miocene, although no positive evidence of such great age has been secured for any of them. If the Big Blue was derived from a serpentine "upthrust" on Joaquin Ridge, it is necessary to assume that the margin of the serpentine mass was faulted as early as Middle Miocene time, but of course it is not probable that the faults developed then were those that now bound this serpentine mass. It is more probable that those faults are now among the undistinguished mass of faults that cut this serpentine body, and that the present marginal faults came into existence later, after a greater area of serpentine had been stripped of its Cretaceous cover by Pliocene erosion.

In summary, the conclusion that much of the folding of the Coalinga district is old is based on a vast amount of incontrovertible evidence, particularly that of the numerous overlaps and unconformities that have impressed all observers and are clearly shown on all geological maps of the district.[49] The faults of the district have also been

[47] R. D. Reed, "Geology of California: Some Corrections," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 19, No. 12 (December, 1935), pp. 1821–24, Figs. 1 and 2.

[48] R. W. Pack and W. A. English, "Geology and Oil Prospects in Waltham, Priest, Bitterwater, and Peachtree Valleys, California, with Notes on Coal," *U. S. Geol. Survey Bull. 581-D* (1914).

[49] See, *e.g.*, Plate 89 in B. L. Clark, "Tectonics of the Mount Diablo and Coalinga

thought to be old, and to have formed the folds during the Pleistocene by a process called "drag." The writers have seen nearly all the field data cited in favor of this concept, but do not believe that any of it is valid. They must therefore content themselves by stating the facts as they appear, and by referring those interested in the "drag" concept to the publications in which it is expounded.[50]

GEOLOGY OF OTHER PARTS OF THE NORTHERN GEOSYNCLINAL BASIN

Several features in the part of the old Northern Geosynclinal basin south of the Coalinga district are interesting, but none of them except the Maricopa Basin needs special consideration here. The south end of the San Joaquin Valley lies at the apex of the basin and seems to encroach upon the granitic mass to the south in the boundary region between Mohavia and Salinia. Lower Cretaceous, Upper Cretaceous, and Paleocene deposits are now missing from the southern boundary of the basin and their former extent is a matter of speculation. The writers prefer to assume that Upper Cretaceous and Paleocene strata once covered the whole area and that the Lower Cretaceous never did so, but other opinions are not excluded by the facts now known. Whatever the facts may be about the distribution of these earlier formations, those of Eocene, Oligocene, Miocene, Pliocene, and Pleistocene age are certainly represented, most of them in thicknesses not much less than the maximum for the Coast Ranges. The Maricopa Basin must therefore be considered one of the largest and deepest in Southern California during post-Paleocene time.

It is important to notice, first, that this basin lies exactly at the apex of the old Northern Geosynclinal basin and second, that the locus of greatest subsidence seems to have advanced southward between Franciscan and Eocene time, but to have receded northward again after the Miocene. An inspection of the paleogeographic maps will illustrate these points, the second of which is not demonstrable because of the impossibility of determining accurately the boundaries of Franciscan and Cretaceous in this area.

Areas, Middle Coast Ranges of California," *Bull. Geol. Soc. America*, Vol. 46 (1935), p. 1025.

[50] For an early and simple statement, with illuminating diagrams that deserve close study, see B. L. Clark, "Tectonics of the Valle Grande," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13, No. 3 (March, 1929), pp. 199–238. For a more recent statement that omits many of the claims of the earlier paper and advances new ones, chiefly relating to minor details said to be visible along the supposed faults, see the same author's "Tectonics of the Mount Diablo and Coalinga Areas, Middle Coast Ranges of California," *Bull. Geol. Soc. America*, Vol. 46 (1935), pp. 1025–78. For some arguments in the negative, see R. D. Reed, *Geology of California*, Chap. 2, and "Geology of California: Some Corrections," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 19, No. 12 (December, 1935), pp. 1819–24.

CHAPTER IV

MOHAVIA

Whether or not the San Joaquin embayment encroaches upon Mohavia, there is no doubt that the eastern San Joaquin Valley is definitely a part of it. The Sierra Nevada is another, and so are the Basin and Range province north of the Garlock fault, the Mohave Desert proper, the San Gabriel and San Bernardino mountains, the Colorado Desert and the Peninsular Ranges. Even the foothills north and east of Los Angeles Basin belong definitely to this great province with its basement of granitic rocks.

The structural relationship of the Sierra Nevada to the San Joaquin Valley is best seen in the foothills of the Mother Lode district, where the valley has been generally recognized to be the submerged margin of the Sierra Nevada peneplain. Deep wells, such as one recently drilled by the Pure Oil Company northwest of Fresno, have demonstrated that at least the eastern half of the valley in this latitude is properly so described. Farther south there is a series of faults along the boundary between mountain and valley. They are best known near Bakersfield, where their importance for oil accumulation has made them the subject of intensive study. Many large faults, mostly of the reverse type, are also known in the foothills at the south end of the valley. The farther south we go along the east side of the valley, as a matter of fact, the larger and more numerous faults do we find.

This well-known fact seems to be related to the opposing "plunges" of Sierra Nevada and San Joaquin Valley, considered as simple folds. The Sierra Nevada plunges northward, the batholith being more broadly exposed south of Mariposa and Yosemite Valley than farther north. The San Joaquin Valley, on the other hand, has a much thicker and more continuous series of sediments near the south end than in its northern half. It is perhaps justifiable to assume that the marginal faults of the Bakersfield region and farther south developed in response to the strain produced by the diverging tendencies, upward and downward, of the areas east and west of this boundary zone.

The part of Mohavia east and south of the Sierra Nevada is too large, too complex, and too little known to be discussed here in any detail. Since a previous brief statement of the views held by the writers on the Tertiary history of this region[51] has failed to carry

[51] R. D. Reed, *Geology of California*, Fig. 38, pp. 186, 202, *et cetera*.

conviction to some readers, it may be worth while to summarize at some length the views recently expressed on this subject, as a result of extensive observations carried on over a period of years, by C. D. Hulin.[52]

The Searles Lake district, studied by Hulin, has a thick Paleozoic sedimentary series with "all of the more common types of sediments —conglomerates, sandstones, shales, limestones, and cherts." The early Mesozoic is thought to be represented by a sequence of lavas. Near the end of the Jurassic occurred a great batholithic invasion, the same that is well known from its effects in the Sierra Nevada.

> The Sierra Nevada of that time can hardly be pictured as even similar in extent to the present Sierra, since the batholithic invasion involved not only much of the area of the present Sierra Nevada but an almost equally great area in the Tehachapi Mountains and in the desert ranges to the east and south of the present Sierra.

At the time of the batholithic invasion the Searles Lake region may have been mountainous, though the Paleozoic strata are still either flat-lying or slightly folded. Only near the contacts with granitic rocks are they intensely metamorphosed. The granitic rocks themselves are cut by innumerable aplite dikes and by fewer dikes of pegmatite and lamprophyre. Locally these dikes are themselves cut by numerous dikes of a different texture, which seem "distinctly later than the late Jurassic granitic rocks." They are certainly pre-Middle Miocene, and are tentatively referred to early Eocene.

> Subsequent to the batholithic invasion at the close of the Jurassic . . . the Searles Lake quadrangle and adjacent areas were subjected to more or less continuous erosion until about the middle of the Miocene. Whatever the relief may have been at the beginning of the Cretaceous, by early Miocene time this relief had been worn down until the surface at least approximated a peneplain. The thickness of material removed by erosion during this lengthy interval can only be conjectured. To judge from the extent of the quartz monzonite now exposed, from ten to twenty thousand feet of rock may well have been eroded away. All of the products of erosion were removed from the region so that a well-developed external drainage system must necessarily have been in existence . . .

In about Middle Miocene time the northern Mohave Desert region was affected by warping and faulting, with the resultant formation of elevated mountain blocks and depressed basins and a complete destruction of the pre-existent drainage system. The conditions brought about by this event led to the accumulation of the Rosamond series in the depressed basins. It is composed of coarse to fine, angular ma-

[52] Carlton D. Hulin, "Geologic Features of the Dry Placers of the Northern Mohave Desert," *California Jour. Mines and Geol.* (1934), pp. 417–24.

terial derived from uplifted areas near at hand. Many of the clays are colored green, red, brown, or yellow, and some of them include saline material.

> The sedimentation of the lower Rosamond was interrupted by a widespread volcanic outburst which apparently affected the whole desert province, and which can unquestionably be correlated with volcanic outbursts of other parts of the Great Basin. The opening phase of the volcanic activity was of the explosive type, and apparently the whole region was blanketed with a thick mantle of tuff . . . Locally the formation of this tuff horizon was accompanied and followed by the accumulation of agglomerates, the pouring out of lava flows, and the injection of dikes and plugs. The volcanic activity appears to have been of the fissure type . . . The nature of the volcanic activity appears to have varied from time to time and from place to place, rhyolites, dacites and rather acidic light-colored andesites and their pyroclastic equivalents all being represented.

The later Rosamond beds have much volcanic detritus, but become more and more arkosic toward the close of the period of sedimentation.

The age of the upper part of the Rosamond, as determined from mammalian fossils found at Barstow and elsewhere is Middle or Upper Miocene. The age of the lower Rosamond is unknown, but is believed by Hulin to be no older than early Middle Miocene.

Flows of basic, dark-colored andesites occur throughout the northern Mohave Desert, and rest either upon the Rosamond or upon any of the pre-Tertiary basement rocks. Pebbles and boulders of these andesites occur in the basal part of the Ricardo series, which is considered by Hulin and by many vertebrate paleontologists to be Lower Pliocene in age, but is here referred to the Upper Miocene. In any case, as Hulin states, the andesites are clearly referable to the Upper Miocene.

The detritus of the Ricardo beds is believed by Hulin to have been brought to the region by a large river system, draining from a more northerly region, and bringing in rounded boulders of resistant rocks, many of them foreign to the Searles Lake region. This drainage system was destroyed by renewed faulting and volcanic activity.

> In several portions of the region important accumulations of tuffs, with some interbedded arkosic sediments, agglomerates, and flows of andesite, showing a finely developed flow structure, overlie the basal conglomerates. These grade upward into more basic tuffs and flows of olivine basalts.

Locally, as at Red Rock Canyon, the olivine basalts are overlain by great thicknesses of poorly sorted arkosic sands and angular gravels, which are of local origin.

In post-Ricardo time the history of the region has been largely

one of erosion, but the faulting of Pleistocene and perhaps late Pliocene time has developed the present fault-block mountains and depressed basins. The post-Ricardo gravels sometimes resemble those of the basal Ricardo, but may be distinguished by their content of olivine basalt pebbles.

Part of the interest and importance of Hulin's work lies in the correlation it suggests between the events of this region and those of the Sierra Nevada, with its late Jurassic batholithic invasion, Cretaceous and Eocene erosion, and Miocene "rhyolitic" and "andesitic" series. That a similar correlation is possible between the northern Mohave district and some other parts of Mohavia may be learned from another recent publication,[53] which deals with the western end of the Mohave Desert and adjacent areas north and south. This region seems to lack post-Rosamond Tertiary rocks, and contains littoral Paleocene beds, but is similar in most other respects to the area studied by Hulin. Much the same may be said for the San Gabriel and San Bernardino mountains and for the other known parts of the desert of southeastern California. All are so similar in lithologic features, structure, and implied history as to leave little doubt that their differentiation into geologic subprovinces is an event of middle to late Cenozoic. The name "Mohavia" was invented to stress this important fact.

The Elizabeth Lake Quadrangle and the Tejon Quadrangle which adjoins it to the west serve as a connecting link between Mohavia and its Coast Range dependency, Salinia. The northern part of the Tejon Quadrangle—that is, the foothills at the south end of the San Joaquin Valley—are well known as a result of several investigations made by members of the United States Geological Survey.[54] The central part of the quadrangle has been studied by J. P. Buwalda, whose results are incompletely published. The southern part, lying north of the Saugus-Newhall district, has been mapped and studied by Thomas Clements, whose map and notes have been available to the writers.[55] Perhaps the most interesting feature brought out by Clements is the occurrence of several great faults, on one of which there is considerable evidence of recurrent movement during the Tertiary and later.

[53] E. C. Simpson, "Geology and Mineral Deposits of the Elizabeth Lake Quadrangle," *California Jour. Mines and Geol.* (1934), pp. 371–416.

[54] *Cf.* H. W. Hoots, "Geology and Oil Resources along the Southern Border of San Joaquin Valley, California," *U. S. Geol. Survey Bull. 812-D* (1930).

[55] Dr. Clements plans to publish a map and discussion of this area at an early date.

CHAPTER V

THE CALIENTE MOUNTAIN DISTRICT AND SALINIA

In structure and stratigraphy Salinia differs markedly from all adjacent provinces except Mohavia, from which it differs chiefly in the greater degree to which it was flooded by the sea during several post-Jurassic transgressions. The boundary between Mohavia and Salinia is not very definite, but may be arbitrarily considered to run across the Tejon Quadrangle from Grapevine Canyon to Saugus or Piru; that is, from the southeast boundary of the Maricopa Basin to the east end of the Ventura Basin. Topographically, Salinia resembles Mohavia in being divided into so many provinces—Carrizo Plain, Cuyama Valley, La Panza Mountains, Paso Robles Basin, Gabilan Mesa and others—that its essential unity has not always been appreciated. Structurally it resembles Mohavia in being divided into several blocks, with bounding faults nearly parallel, as they are in some parts of Mohavia. All the other resemblances, stratigraphic, structural, and topographic, are presumably related to the fundamental similarity in basement rocks; that is, to the presence of a granitic basement and to the absence of the Franciscan series.

The part played by Salinia in the structural evolution of California will appear from a brief account of the historical geology of Caliente Mountain and the adjacent lowlands to the north and south. These lowlands are Carrizo Plain, an enclosed basin 2,000 feet above sea-level, and Cuyama Valley, nearly enclosed and with about the same elevation, but drained across the San Rafael Mountains by the Cuyama River. The Caliente Mountains constitute an elongated ridge trending northwest-southeast between these lowlands. Its highest peak, Caliente Mountain, is 5,095 feet high, its average axial elevation perhaps 3,000–3,500 feet (Fig. 28).

These three topographic units constitute a cross-section of Salinia, from its northeastern boundary, the San Andreas fault, to its southwestern margin at the Cuyama fault, which is the southern continuation of the Nacimiento fault zone.

CALIENTE MOUNTAIN REGION

The Caliente Mountain region has the excellent outcrops characteristic of a mountainous area in a semi-arid climate and has long been known to contain one of the thickest and most varied Miocene sections in California and to possess many other features of great

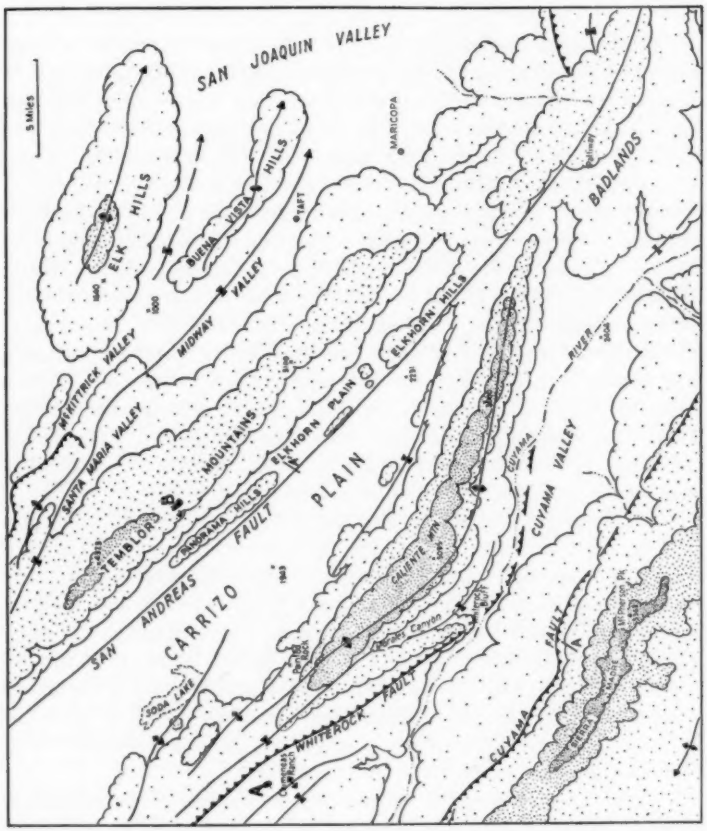


FIG. 28.—Map of Caliente Mountain and adjacent territory. Symbols as in Figure 24. The part of the area northeast of the San Andreas fault is the Maricopa Basin. *A* and *B* are small outcrops of granitic basement.

geological interest. In spite of this fact and in spite of the fact that a good topographic map has long been available, the area has been much less studied than many other parts of Southern California. Published references to the geology are in fact few and most of them treat only of minor details. Arnold and Johnson made a brief reconnaissance[56] of Carrizo Plain and showed a few of the more important structural features along part of its west margin on their geological map. W. A. English made a reconnaissance[57] of the Cuyama Valley region, but considered the oil possibilities too remote to justify detailed mapping or extensive discussion. His colored geological map includes Caliente Peak and part of the southwest flank of the mountain, as well as Cuyama Valley. Like all other workers in the area, English was much impressed by the varied lithology of the Miocene strata. He made an effort to classify the different facies into the Miocene formations that were recognized at the time of his study, but the difficulties were too great to permit of complete success. In the western part of Cuyama Valley, for example, his "Santa Margarita formation" locally includes strata referred by later workers to Oligocene (?) red beds, Lower Miocene Vaqueros, Middle Miocene, Santa Margarita, and a later formation probably equivalent in age to the Pliocene or Pleistocene Paso Robles formation. So thin are the different Tertiary formations in this area (Fig. 29), however, that all of them taken together do not exceed the thickness of the Santa Margarita in some adjoining parts of the region.

In their endeavor to disentangle the confused stratigraphy and structure of this area, the present writers have been under obligations not only to the geologists already mentioned but also to many more recent workers,[58] most of whose results are unpublished.

Most of the data important in the present connection are shown in some of the accompanying maps and diagrams. The text will be limited to some notes on certain points in which this area resembles or differs from the Coalinga district.

PRE-MESOZOIC FORMATIONS

"Granite."—Outcrops of basement rock in the area of Figure 28 are two: one near the west margin, on Chimeneas Ranch; the other

[56] Ralph Arnold and H. R. Johnson, "Preliminary Report on the McKittrick-Sunset Oil Region, Kern and San Luis Obispo Counties, California," *U. S. Geol. Survey Bull. 406* (1910).

[57] W. A. English, "Geology and Oil Prospects of Cuyama Valley, California," *U. S. Geol. Survey Bull. 621-M* (1916), pp. 191–215.

[58] Particular acknowledgments are due to J. E. Eaton, C. L. Gazin, U. S. Grant IV, A. I. Gregersen, D. D. Hughes, W. D. Kleinpell, Howard Pyle, and Max Steineke.

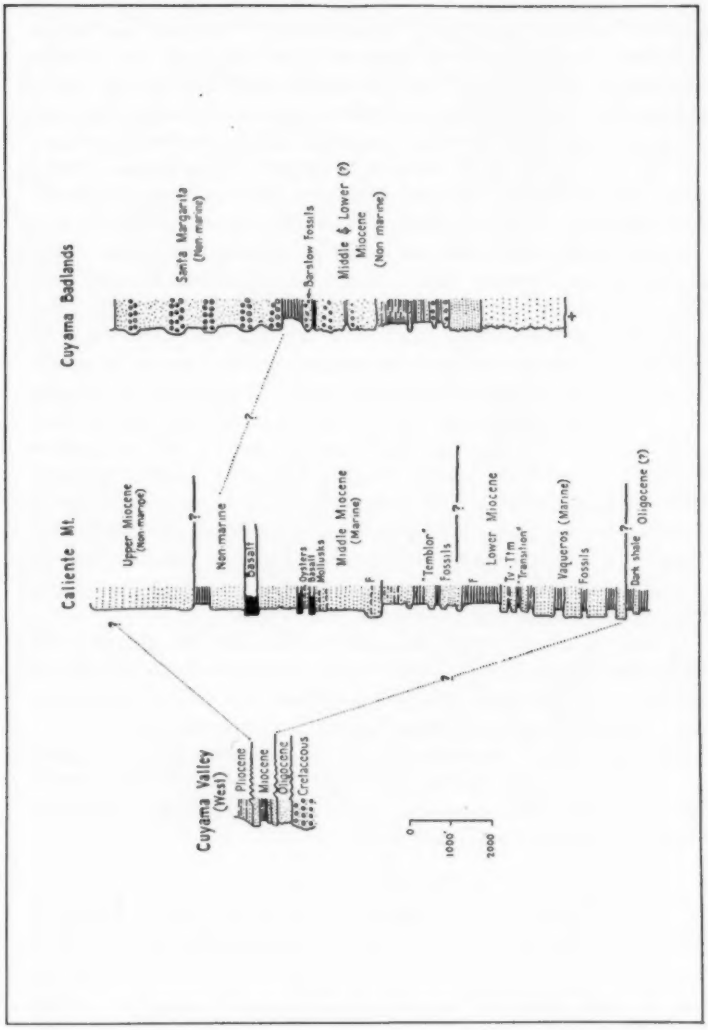


FIG. 29.—Columnar sections of Caliente Mountain district.

in the Temblor Mountains northeast of Panorama Hills. The latter is interesting because it lies northeast of the San Andreas fault, and is farther northwest than any other granitic outcrop near that fault and on its northeast side. A short distance north of the mapped area, as a matter of fact, Franciscan rocks occur near the fault on the northeast side and granite not far away on the west side. The Chimeneas Ranch outcrop is an outlier of the extensive mass of granitic rocks of the La Panza Mountains, several miles west of the northwest corner of the area mapped. These outcrops of granitic basement include not only granitoid igneous rock but also associated quartzite, schist, and coarsely crystalline limestone. The age of the granite is supposed to be either late Paleozoic or Jurassic, but different parts of it may perhaps date from both periods—perhaps from both the Appalachian and Nevadian revolutions.

MESOZOIC FORMATIONS

Cretaceous.—The beds mapped as Cretaceous have yielded no fossils and may thus include members of any age from Upper Jurassic to Eocene. From lithologic and other considerations the writers suspect that most of the beds so classified are actually Upper Cretaceous, but that some of them may be Paleocene. They include beds of conglomerate, sandstone, and sandy shale. Pebbles of the conglomerates are in general moderately well rounded and consist of porphyry, basalt, granite, and other non-Franciscan rock-types. The sandstone is medium-grained and arkosic, the shale sandy or silty. Structurally the Cretaceous is fairly strong and rigid and seems to have taken part in diastrophic movements much as if it formed part of the basement; that is, it is either faulted or warped into broad folds.

CENOZOIC FORMATIONS

Eocene.—Many thousands of feet of Eocene strata are found in the mountains south and east of Cuyama Valley but none is exposed, so far as known, within the part of the area of Figure 28 southwest of the San Andreas fault. A small patch of dark shale found at the core of Caliente Mountain anticline might possibly be Eocene, but is for the present referred to Oligocene. Since a few thin erosional remnants of Middle or Upper Eocene are known from other parts of the Salinian "axis" there is a distinct possibility that if the oldest exposed Caliente Mountain beds are Oligocene, they may overlie Eocene beds which fail to crop out anywhere in the area. Only deep drilling could decide this point, which is important for its bearing on the origin of the Caliente trough, discussed on a later page of this chapter.

Oligocene.—The strata classed as Oligocene belong to two facies. One is the red-beds facies, commonly classed as the Sespe formation. Here belong English's "Redrock Canyon member" of his Santa Margarita, and his "Pato red member" of the Vaqueros. In the Cuyama River gorge immediately west of Cuyama Valley, the Sespe is largely conglomeratic and reaches a thickness of perhaps 2,000 feet, but in Cuyama Valley itself the thickness is commonly much less. Red Sespe beds are also found along the northward continuation of Caliente Mountain ridge, west of Soda Lake. They are here associated with a thick series of sparingly fossiliferous sandy shale, which, like the similar sandy shale found in the core of Caliente Mountain anticline, is referred to the Oligocene without adequate paleontologic proof. It may be as young as Lower Miocene or as old as Eocene.

Miocene.—Toward the southeast the Caliente Mountain ridge grades into a badland district several miles wide and perhaps 30 miles long. The district is shown, in part, on English's map, and has been studied more intensively by Gazin.[59] The badland rocks consist of two thick series of coarse material separated by a brown shale member a few hundred feet thick. The shale member can be traced all through the badland district, and is probably correlative with a persistent shale bed on the northeast flank of Caliente Mountain ridge. In sandstone not far below the shale Gazin found most of his mammalian fossils, correlated with the Barstow fauna of the Mohave district. Beneath the supposed correlative of this shale near Caliente Mountain, scraps of bone have been found but nothing identifiable as yet. Since bone horizons as well as shale members are exceedingly scarce in these beds, the sequence suggests that Gazin's fauna belongs beneath the persistent shale member of Caliente Mountain. This correlation puts it at the top of the series of conglomerates and interbedded flows that rests upon marine beds containing lower Middle Miocene fossils.

The persistent shale of Caliente Mountain has been correlated by Eaton[60] with the Whiterock marine member of the Miocene southwest of Caliente Mountain. The evidence for the correlation is not decisive but the correlation is not improbable. If it is correct, Gazin's mammalian fossils, and the Barstow fossils as well, belong in the Middle Miocene of the California marine section, as it is now divided. This correlation is not in harmony with ideas expressed in the older

[59] C. L. Gazin, "Tertiary Mammalian Fauna from Upper Cuyama Drainage Basin," *Carnegie Inst. Washington Pub. 404* (1930), p. 55–76.

[60] Personal communication.

PLATE IV.—Looking south at Temblor Range (near left), Carrizo Plain with Soda Lake, Caliente Mountain Ridge. Beyond is Cuyama Valley, with Big Pine and Madulce ridges (San Rafael Mountains) in background. The San Andreas fault shows clearly between the Temblor Mountains and Carrizo Plain. Photo by Erickson.

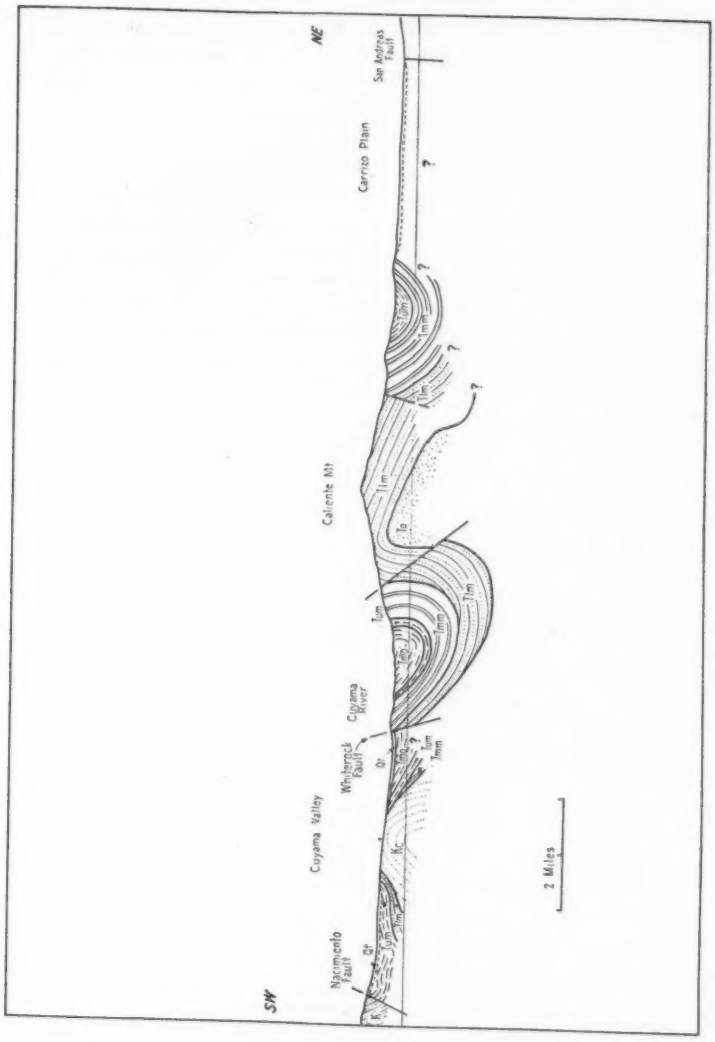


FIG. 30.—Structure section across Caliente Mountain. Drawn along a different line from that followed by Eaton's section, Figure 29 of *Geology of California*.

literature, but should be compared with the conclusions of more recent papers, such as that of Bode.[61]

The Caliente Mountain section is marine in the Lower Miocene and lower Middle Miocene parts, littoral above lower Middle Miocene, and nonmarine throughout the several thousand feet of beds belonging to upper Middle and Upper Miocene. Toward the southeast, Lower and lower Middle Miocene grade into littoral and then nonmarine facies. Toward the northwest, on the other hand, all members become marine, and most of the Lower and Middle Miocene becomes foraminiferal, commonly siliceous, shale. The great difference in facies of these beds permits the determination of the interrelations of mammalian, mollusk, and foraminiferal zones, a task that is not easy in many districts. Further paleontological study of the Caliente Mountain area in the interest of these problems is greatly needed.

Pliocene.—Marine Pliocene strata, though present in the Paso Robles Basin to the northwest, are not found in the Caliente Mountain region. The nonmarine Morales formation, referred by W. A. English to the Upper Miocene, consists of coarse sands and barren sandy clays containing many fragments of Miocene siliceous shale. Though it lies discordantly on older strata including the Santa Margarita, this formation is itself notably folded and faulted. In all respects it seems to be analogous to the Paso Robles formation, Upper Pliocene (?) and Lower Pleistocene, of the Paso Robles Basin, and may be of the same age.

English's Cuyama formation, though slightly deformed, seems likely to be Upper rather than Lower Pleistocene. Some other sands and gravels found on uplifted terraces may also be Upper Pleistocene.

The Morales formation is found in Cuyama Valley, in the lower parts of the Caliente Mountains, and probably exists under cover in Carrizo Plain. The Cuyama and other similar formations occur in the Cuyama Valley.

SUMMARY

In summary, the Caliente Mountain region is characterized by a granitic basement which is overlain, at least in the Cuyama Valley part, by a massive conglomeratic formation of Cretaceous or Paleocene age. The Tertiary strata are chiefly Miocene in age. All stages of the Miocene are represented and each stage is present in marine, littoral, and nonmarine facies. Thicknesses range from a few hundred

[61] F. D. Bode, "The Fauna of the Merychippus Zone, North Coalinga District, California," *Carnegie Inst. Washington Pub. 453* (1935), p. 85.

PLATE V.—Looking north across Cuyama River at Caliente Mountain. One of the thickest and most interesting Miocene sections in California is well exposed on these barren slopes.

to several thousand feet, and the changes in thickness from place to place are strikingly abrupt. The Pliocene is nonmarine.

The problems of structural evolution may be introduced by an examination of the structure sections of Plate I and Figure 30. Since little deep drilling has been done in this district, these sections show subsurface conditions only as they may be deduced from a study of surface data. The most obvious conclusion to be drawn from the sections is that the Caliente Mountain belt differs from the Carrizo Plain and Cuyama Valley belts in possessing larger and stronger folds, some of which are thrust-faulted. There is thus an apparent relation between thickness of sedimentary cover and nature of folding, the belt of strong deformation being that of thick strata.

Another interesting feature revealed by the sections is the existence of overturning and overthrusting along each margin of the belt of thick strata. In each case, moreover, the overturning and overthrusting is toward the nearest belt of thin strata. Thus, the Morales syncline is overturned toward Cuyama Valley, and the Whiterock fault is thrust in the same direction. The smaller Goat Springs fault on the north flank of the Caliente Mountain is thrust toward Carrizo Plain and the syncline to the northeast is overturned in the same direction. Another way of expressing the relation is to say that the folds and thrust faults indicate a surface movement toward the adjacent stable areas. This principle is exemplified in many places, in the Caliente Mountain region and elsewhere, but exceptions are also found. In this region, for example, one small but prominent anticline is steepest on the flank adjacent to the Caliente Mountain belt of thick sedimentary rocks.

The existence of a long, narrow belt, such as Caliente Mountain, between belts of similar width and length but with much thinner blankets of sedimentary rocks, suggests interesting speculations as to the cause. Allowing for crustal shortening during the Pleistocene deformation, the Caliente Mountain province may have been ten miles wide in Miocene time. Its exact length is unknown, but is several times as great as its width. During the Miocene this narrow strip sank approximately 2½ miles, while the adjacent belts north and south sank, on the average, perhaps ½ as much. Did the greater subsidence of the central trough occur with marginal faulting or with warping?

If the intermediate belt had sunk while the adjacent belts were rising a study of Miocene detritus might be helpful, but as a matter of fact, in the region near Caliente Mountain at least, all three belts sank. In Cuyama Valley, for example, Lower, Middle, and Upper

Miocene are all locally represented, and in some places all occur together, but with a total thickness only $\frac{1}{3}$ or locally as little as $\frac{1}{10}$ that of the thickness in Caliente Mountain.

Unless detailed investigations bring new light in the future, it seems that the question of warping versus faulting must be answered either by the unsatisfactory method of mechanical speculation, or by analogy with other regions where the evidence is clearer.

The Coast Ranges furnish adequate proof that sedimentary masses overlying granite may be warped, and strong suggestions that the granite warps similarly.[62] It is thus not obviously impossible that the Caliente Mountain trough developed by warping. In Mohavia, on the other hand, many Miocene basins have been described as due to subsidence along faults. Even in the intermediate area between Mohavia and Salinia, Clements finds evidence of recurrent Tertiary faulting. It is thus not improbable that the Caliente Mountain trough developed as a graben. The writers incline to this view but are constrained to admit that the evidence available to them does not prove it.

Another problem of great difficulty relates to the origin of the San Andreas fault, which serves in the area north of the central Temblor Range as the boundary between Salinia and the Northern Geosynclinal basin. This problem cannot be discussed adequately at present, but neither can it be passed over without mention.

If the views previously expressed as to Lower Mesozoic paleogeography are correct, it follows that the northern part of the course of the San Andreas fault was marked out, though not necessarily followed by a fracture, before the late Jurassic. It was then a boundary between a negative and a positive area. The Nevadian orogeny may have affected this boundary but there is no present way to tell just what the effect may have been. During the Cretaceous the boundary as well as the provinces it separates may have been mantled with sediments, or perhaps Salinia remained partly above sea-level. On the latter supposition, the San Andreas line, faulted or not, may have been a shoreline.

With the oncoming of the folding at the end of the Cretaceous there was developed a series of plunging *en échelon* anticlines in the western part of the Northern Geosyncline. The Joaquin Ridge area, already described, became the site of one of these folds. They seem to have originated near the boundary (the line of the San Andreas)

[62] See, for example, M. L. Hill, "Structure of the San Gabriel Mountains North of Los Angeles, California," *Univ. California Pub. Geol.*, Vol. 19 (1930), p. 158.
Even more striking examples than those described by Hill are known from the central Salinas Valley, but none has yet been described in print.

and to have plunged eastward across the geosynclinal basin. The existence of this *en échelon* series in early Tertiary time, or even before the Tertiary, might be held to prove that shearing stresses became active very early along the boundary between Salinia and the geosyncline. Whether or not this inference is reasonable, the fact remains that the sinking of the area to the east and the rise of Salinia during the whole of the Tertiary, may have brought into existence stresses that had some effect on the localization of the San Andreas fault.

That they were not the sole cause of the fracturing is, of course, very probable, since the fault continues southeastward with all its important characteristics unchanged for more than 200 miles beyond the point where these conditions existed.

As compared with the Coalinga district, the Caliente Mountain area shows many differences in structure and in structural history, some of which are summarized in the diagrams, Figures 49–51. The more positive areas, such as Cuyama Valley, differ greatly both in geologic history and in present topography and structure from such a positive area as the Diablo uplift; and equally great differences exist between the Caliente trough and the San Joaquin embayment; for example, the Diablo uplift is topographically high and Cuyama Valley low, though both were positive during the Tertiary.

CHAPTER VI

THE SAN RAFAEL AND SANTA YNEZ MOUNTAINS

Central Geosynclinal Basin

At the beginning of the Tertiary period folding movements brought the San Rafael uplift into existence in the area of the old Central geosynclinal basin, but left a basin along the south margin and particularly near the landward apex. The basin as a whole will be referred to as the Santa Barbara embayment, the apical part as the Ventura Basin. These subprovinces, San Rafael uplift and Santa Barbara embayment (including Ventura Basin), persisted, though not without important changes, throughout the Cenozoic era. The San Rafael uplift was flooded, at least in large part, during each of the major Tertiary transgressions but underwent elevation and erosion during the regressive periods. The Santa Barbara embayment seems to have subsided continuously but not at a uniform rate. The blanket of sediments deposited in its western part is now well exposed in the Santa Ynez Mountains, which lie along its north margin. Ventura Basin gradually became restricted in area, especially after the Oligocene. So many parts of it were strongly uplifted during Pleistocene and earlier disturbances that the thick formations deposited during the different Tertiary epochs can now be readily examined. The most persistently negative area lies east of the plunging southeast end of the axis of the San Rafael uplift. Part of this negative area seems to lie east of the limits of the Lower Mesozoic geosyncline. In other words, the embayment seems to have developed not only in the margin of the geosyncline, but also on the neighboring granitic province.

The more important aspects of the post-Franciscan history of the old basin may be illustrated by a description of two areas: the Santa Ynez-Santa Barbara area, which includes part of the San Rafael uplift and of its southern border; and the Ventura Basin.

Santa Ynez-Santa Barbara Area (Fig. 31)

From south to north, the area consists of, first, the modern Santa Barbara Channel, lying within the Tertiary Santa Barbara embayment; second, the Santa Ynez Mountains, consisting of a single high ridge east of Gaviota Creek, and of several low ridges farther west; third, the eastern part of the triangular Santa Maria lowland, which is crossed from east to west by low anticlinal ridges that become crowded together east of the village of Santa Ynez; fourth, the high,

PLATE VI-A.—Looking west along Big Pine Mountain ridge. Cretaceous strata dipping northerly toward the Sisquoc River.

PLATE VI-B.—Looking east at Big Pine Mountain, the highest peak of the San Rafael Mountains.

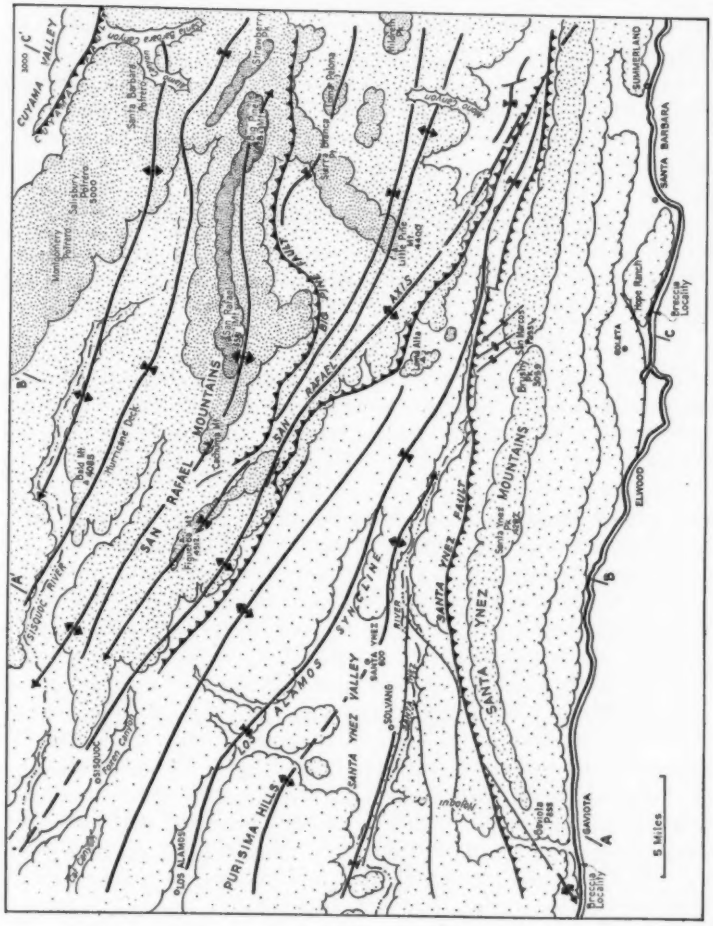


FIG. 31.—Map of Santa Ynez-Santa Barbara district. Symbols as in Figure 24.

rugged San Rafael Mountains; and fifth, a small corner of the foothills along the south side of Cuyama Valley. The west-flowing Santa Ynez River separates the Santa Ynez Mountains from the triangular central lowland, the so-called Santa Maria district. The course of this river also coincides with the approximate boundary between the uplift to the north, and the embayment to the south. The only other stream of considerable size, the Sisquoc River, flows in a narrow valley through the northern part of the San Rafael Mountains. The ridge to the north of the river, distinguished by the presence of several "potreros" (mountain meadows), is sometimes called the Sierra Madre.

This region has been investigated by many geologists, especially during the last ten years. Of the published articles dealing with its geology, mention should be made of those written by Fairbanks, Arnold, Arnold and Anderson, and especially of one by Nelson.[63]

STRATIGRAPHY

The varying stratigraphy of the several parts of the area is indicated in the series of columnar sections (Fig. 32). In most respects, the formations of this area greatly resemble those of the Coalinga district.

Basement rock.—The basement rock is Franciscan, of the same sedimentary, igneous, and metamorphic types as are found in the Franciscan complex of the Coalinga district. Its largest exposures lie along the south margin of the San Rafael Mountains north of Santa Ynez River. Smaller exposures are found in several other localities, some of those best known being west of the area shown in Figure 32. Except for the small corner of Cuyama Valley there is no part of this whole district in which a granitic basement is supposed to be present.

Lower Cretaceous.—Lower Cretaceous has much the same distribution as the Franciscan. As in the Coalinga district, it consists of dark shale and sandstone, with thicknesses up to several thousand feet. Near Little Pine Mountain it seems to lie with an undisturbed depositional contact upon the Franciscan. The basal member here strongly resembles the basal member of the Knoxville where it lies upon the Franciscan northeast of Priest Valley in the Coalinga dis-

[63] H. W. Fairbanks, "Geology of Northern Ventura, Santa Barbara, San Luis Obispo, Monterey, and San Benito Counties," *Twelth Report of State Mineralogist* (1894), pp. 493–526.

R. Arnold, "Geology and Oil Resources of the Summerland District," *U. S. Geol. Survey Bull. 321* (1907).

R. Arnold and R. Anderson, "Geology and Oil Resources of the Santa Maria Oil District," *ibid., Bull. 322* (1907).

R. N. Nelson, "Geology of the Hydrographic Basin of the Upper Santa Ynez River," *Univ. California Pub. Geol.*, Vol. 15 (1925), pp. 327–96.

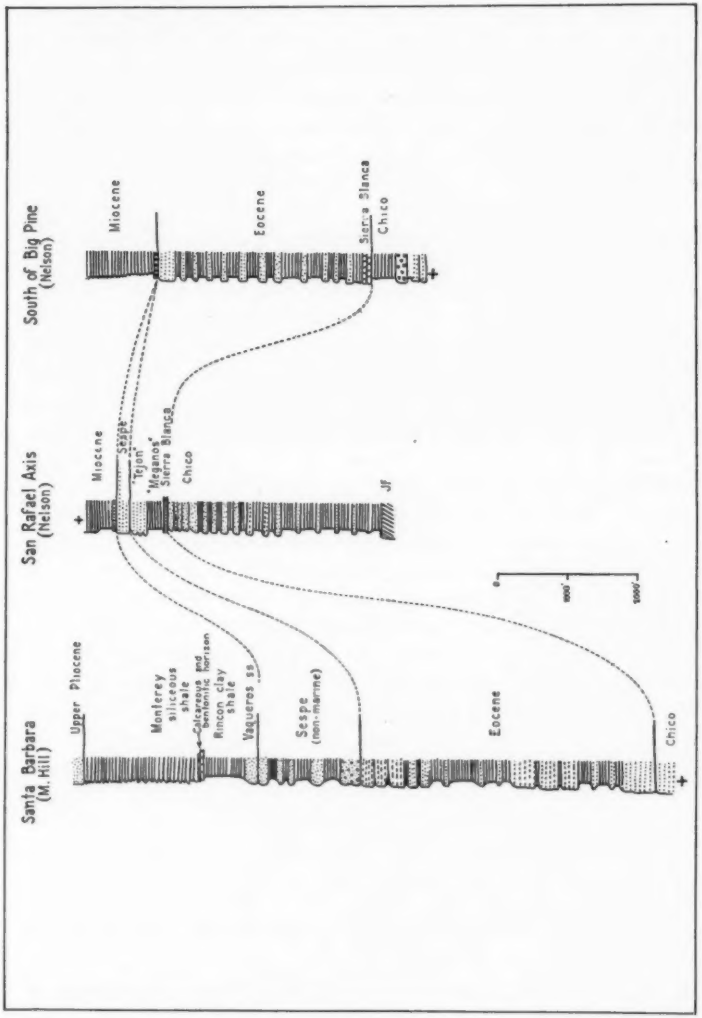


FIG. 32.—Columnar sections of Santa Ynez-Santa Barbara district.

trict. It is a dark, argillaceous shale with innumerable small calcareous concretions. The occasional conglomerate beds that have been observed in the Knoxville contain pebbles of non-Franciscan material.

Upper Cretaceous.—Though absent from most of the triangular Santa Maria lowland, the Upper Cretaceous is well developed in the San Rafael Mountains and also—though not so prominently exposed—along the north flank of the Santa Ynez Mountains. This distribution is important in connection with the concept of a Tertiary San Rafael uplift, and particularly with reference to the date of its initiation.

Like the Knoxville, the Upper Cretaceous of this region seems to lack notable amounts of Franciscan detritus.

Martinez strata are not known in the area, but seem not unlikely to be found associated with the frequently unfossiliferous Eocene and Upper Cretaceous strata of the north flank of the Santa Ynez Range.

Eocene.—The Eocene has a distribution comparable to that of the Upper Cretaceous, being absent from much of the triangular Santa Maria lowland. Its greatest thickness and most prominent exposures are found in the Santa Ynez Mountains, though it is also well developed in the eastern part of the San Rafael Mountains, especially beyond the limits of Figure 31. In many places it lies unconformably upon Upper or Lower Cretaceous, or even upon the Franciscan. In one exposure south of Buellton, it lies with an angular discordance of approximately 30 degrees upon rocks of Cretaceous age. The basal member of the Eocene is in many places a limestone, or a highly calcareous conglomeratic sandstone, the Sierra Blanca limestone,[64] associated with a reddish foraminiferal shale. The younger members of the series are thick shales and sandstones, of which there are about four in the Santa Ynez Mountains and fewer farther north where the thickness is in general much less. The presence of a conspicuous amount of Franciscan detritus, particularly in the Upper Eocene, suggests that the San Rafael uplift may have been re-elevated at some time during the Eocene. The Upper Eocene lacks siliceous shale of the Kreyenhagen type. In other respects, the Eocene of this region is very similar to that of the Coalinga district. The presence of a basal limestone or calcareous member, with similar fossils, in parts of both regions, is particularly striking.

Oligocene.—In the longitude of Santa Barbara, red beds of typical Sespe type are conspicuous both north and south of the Santa Ynez

[64] A good account of this member, with references to earlier publications, may be found in M. F. Keenan, "The Eocene Sierra Blanca Limestone at the Type Locality in Santa Barbara County, California," *Trans. San Diego Soc. Nat. Hist.*, Vol. 7 (1932), pp. 53–84.

PLATE VII-A.—Looking north from Big Pine Mountain across head of Sisquoc River at part of Madulce Ridge. Cretaceous sandstone and conglomerate.

PLATEVII-B.—Looking south from Big Pine Mountain across the rough mountainous region of the San Rafael and Santa Ynez mountains. Santa Cruz Island is faintly visible in the background 50 miles away. Sierra Blanca ridge is the light-colored ridge in the middle distance.

Mountains. Farther north they are absent, and farther west they give way to marine beds which have recently been described as the "Refugian stage."[65] They have some similarity to the beds called Oligocene at the south end of the San Joaquin Valley, but lack the siliceous organic shale that forms a conspicuous part of the "Refugian stage" near Coalinga. Faunal resemblances are close between the Oligocene rocks of the two areas.

Miocene (Fig. 32).—The Miocene strata of this region belong to the Lower, Middle, and Upper divisions. The Lower division includes the Vaqueros sandstone member and the Rincon ("Temblor") clay shale, which in some areas carries sandstone beds with "Vaqueros" fossils. The Lower Miocene is transgressed by the Middle Miocene, the basal member being in many localities a limestone comparable in all respects except fauna to the Eocene Sierra Blanca limestone. At Little Pine Mountain this member is a calcareous sandstone, resting with slight angular discordance upon Knoxville strata. Both Middle and Upper Miocene contain a predominance of siliceous organic shale, including diatomite, chert, and all the other varieties, along with some beds of sandstone. Locally, as near Santa Barbara (Hope Ranch) and at Gaviota Creek, the Upper Miocene includes a thick member of coarse breccia, with fragments of Upper and Middle Miocene chert, limestone, and diatomite. As suggested by Figure 31, this breccia occurs near the plunging south ends of prominent cross-folds of the Santa Ynez Mountains. It immediately overlies foraminiferal beds containing a *Bolivina hughesi* fauna, and underlies silts with a poor fauna considered to be Upper Miocene rather than Pliocene. Its age is thus middle Upper Miocene, and its origin is presumably due to uplift along the cross-folds at this time. Since the east-west structure of the Santa Ynez Mountains cannot be proved to have come into existence until later, it is probable that the site of the future mountains was at that time a south-dipping homocline, fluted by a few low folds with a strike at variance to that which prevailed later. The most important member of this series of cross-folds was the one forming the axis of the San Rafael uplift and extending to Ventura where, as Figure 36 suggests, it is also bordered by an Upper Miocene breccia, presumed but not known to be of exactly the same age as those at Hope Ranch and Gaviota Creek.

Volcanic rocks form an important constituent of the Middle and Upper Miocene along the axis of the San Rafael uplift but are not conspicuous elsewhere. There are a few basic lava flows in the Middle

[65] H. G. Schenck and R. M. Kleinpell, "Refugian Stage of Pacific Coast Tertiary," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 20, No. 2 (February, 1936), pp. 215–25.

Miocene near Santa Ynez, and there is a widespread bentonite at the base of the Middle Miocene nearly everywhere in this area and also in the Ventura Basin. Ash beds occur locally at other horizons but are relatively inconspicuous.

As in the Coalinga district, the Miocene of this area consists of a lower division that is locally transgressed by the middle division, and an upper division that is dominantly siliceous shale. The middle, transgressive division has at its base a calcareous member, but it contains less sand and is generally thicker in the Santa Ynez than in the Coalinga area. No angular unconformity has been described between Middle and Upper Miocene in the Santa Ynez area, but failure to recognize it may perhaps be due to the lithologic similarity of the two divisions rather than to a complete absence of the unconformity.

Pliocene.—Unlike the Coalinga region, this one has comparatively little Pliocene. The thickest section is found west of the area of Figure 31 in the Santa Maria Valley, where the 4,000 feet of beds in the center of the syncline south of Santa Maria thin rapidly to the south, and disappear a few miles to the north. The Lower Pliocene is locally diatomaceous, but in its coarser facies carries a fauna like that of the Lower Pliocene of Coalinga. The Upper Pliocene, on the other hand, carries a fauna like that of the Upper Pliocene of the Ventura and Los Angeles basins. In most of the Santa Ynez region the marine Pliocene is only a few hundred feet thick, and is overlain by a much thicker series of nonmarine sands and gravels with many pebbles of Monterey shale. This material is commonly called "Paso Robles," and like the Paso Robles, Morales, Tulare and Saugus formations of other areas is variously referred to Upper Pliocene and Lower Pleistocene. Along the Santa Barbara coast occur the fossiliferous sands and marls of the Santa Barbara formation, also Upper Pliocene or Lower Pleistocene in age.

Uplifted terraces of possibly Upper San Pedro (Upper Pleistocene) age are found near the coast and along some of the rivers. Some of them have furnished small faunas of mollusks and of horse teeth, all referred to living genera. These terraces were cut after the strong mid-Pleistocene folding movements.

STRUCTURE

The Santa Maria lowland, most of which lies northwest of the area shown in Figure 31, is synclinal at the south, but overlies the axis of the San Rafael uplift, the oldest and most important anticline of the whole province, along its north margin. South of this lowland all the ranges of hills are either upfolded or upfaulted, the valleys are

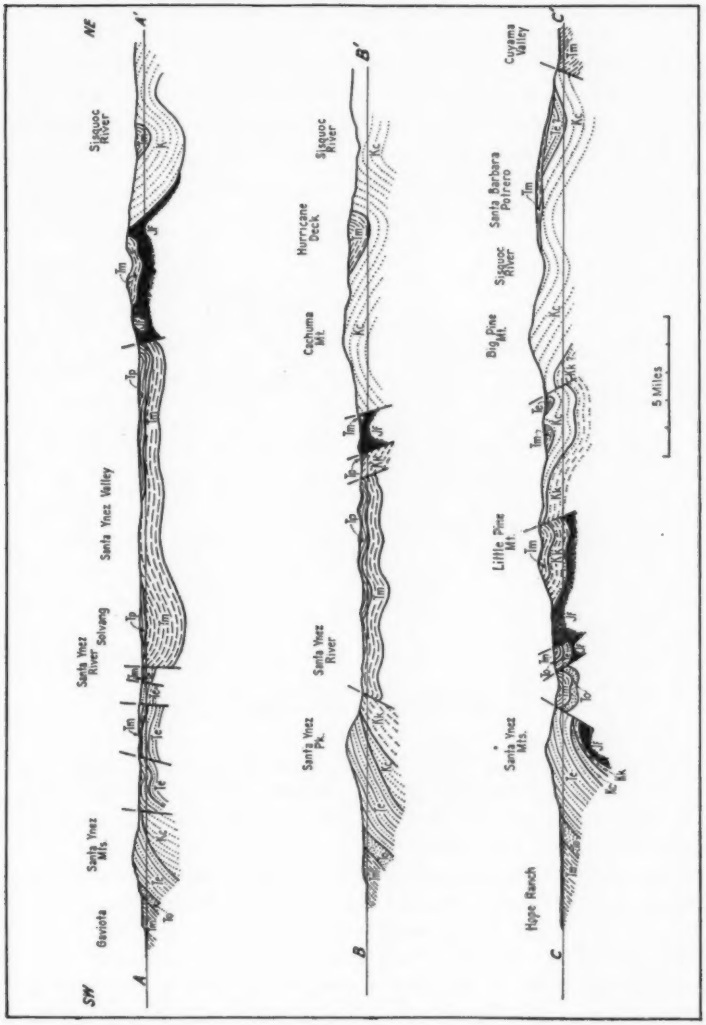


FIG. 33.—Structure sections across Santa Ynez-Santa Barbara district along lines indicated on Figure 31.

either synclinal or down-faulted. The structure is relatively simple between the Santa Maria River at the north, which follows the axis of the San Rafael uplift, and the Santa Ynez River at the south. South of the latter river the structure is complicated. West of Gaviota Pass the Santa Ynez Mountains break up into two or three more or less parallel chains separated by faulted synclines. The area is one of numerous unconformities, the most important of which separates Cretaceous and Eocene strata.

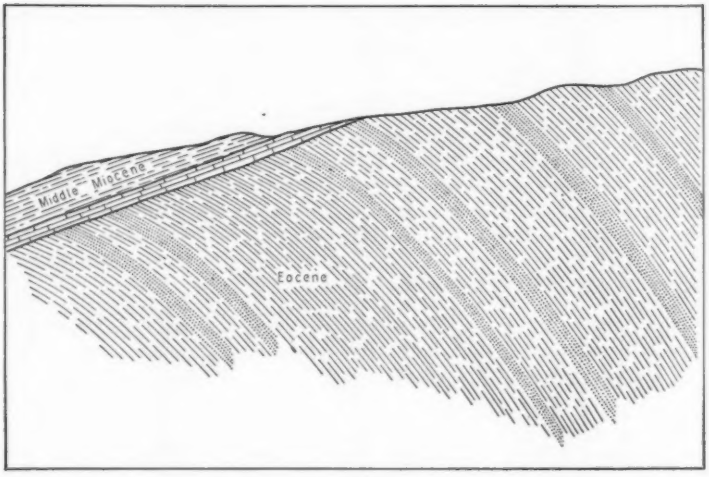


FIG. 34.—Unconformity on Alamo Creek near Santa Barbara Potrero, south of Cuyama Valley. This diagram was sketched from a photograph.

Toward the east the Santa Ynez and San Rafael ranges approach each other and the intervening area becomes extremely complex, the folds being much faulted. An examination of the map and structure sections shows this condition clearly.

Among the structural features deserving more detailed consideration are the Big Pine and Santa Ynez faults, the Santa Ynez Mountains, and the Santa Maria basin (Figs. 33, 34 and 35).

Big Pine fault.—The Big Pine fault is one of the major thrusts of Southern California. It has been traced, though not in detail, from a point not far from Figueroa Mountain to the western edge of the Tejon Quadrangle, near the point where Big Sespe Creek turns south toward the Ventura Basin. Near Big Pine Mountain the upthrown northern side has caused Cretaceous strata to overlie Eocene. Farther

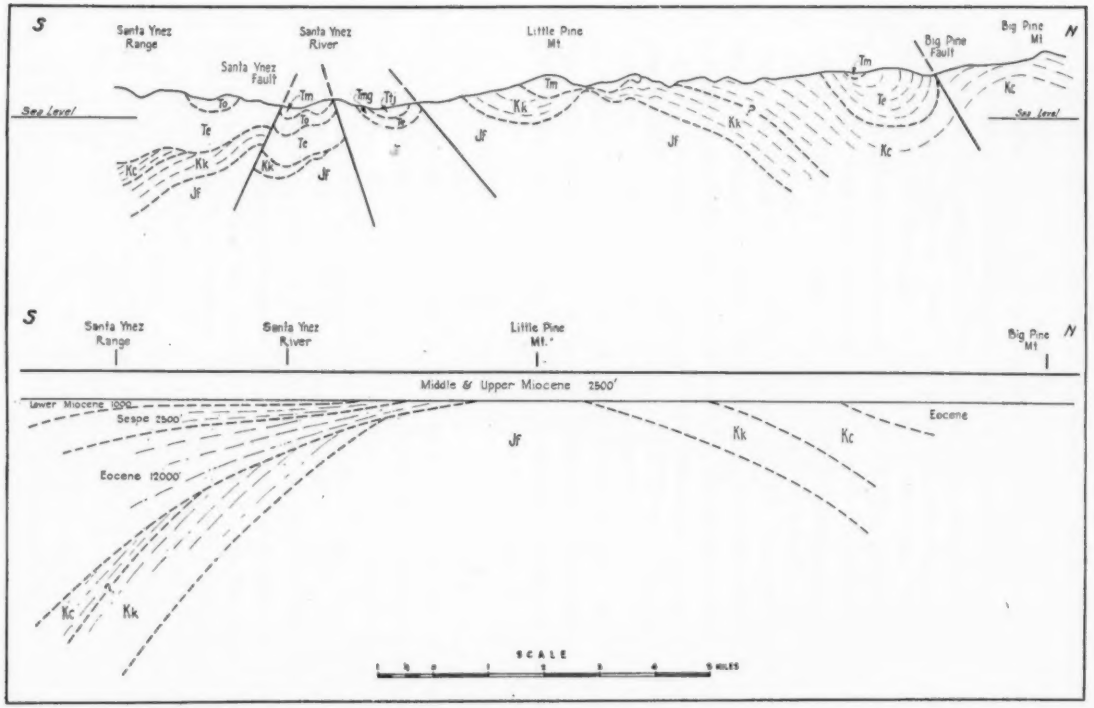


FIG. 35.—Present and Upper Miocene structure, along north-south line in Santa Ynez-Santa Barbara district. Note that Big Pine fault (northernmost of those shown) and Santa Ynez fault (southernmost) have developed near the thin edges of great wedges of resistent strata (Eocene and Upper Cretaceous, chiefly).

east, Eocene strata on the northern side overlie Upper Miocene on the south. The angle of dip of the fault plane is known in only a few places; in these it is not far from 45 degrees.

The origin of this fault is not entirely clear. It lies between the area of immensely thick Cretaceous strata 14,000 feet or more in Big Pine Mountain and the axial part of the San Rafael uplift, where the Cretaceous may have been relatively thin at the time of deposition, and in any case was removed by erosion before the Middle Eocene. It may thus belong to one of the two types discussed later.

It is interesting because it is one of the few examples of a thrust fault that is not directed toward an area that was a basin during the late Pliocene and early Pleistocene.

Santa Ynez fault.—The Santa Ynez fault, which forms the northern edge of the Santa Ynez Mountains east of Gaviota Pass, and splits into two or more branches west of that point, likewise separates an area of thick and continuous Cretaceous-Eocene strata from a thin, discontinuous Cretaceo-Tertiary series. The thick series lies south, the thinner one north, of the line of the fault, and like the Big Pine fault, this one is also thrust toward the region with the thinner sedimentary blanket. Unlike the Big Pine fault, however, it is in much of its course—though not in all—thrust toward an area that was a basin during the later Pliocene and early Pleistocene.

Santa Ynez Mountains.—The Santa Ynez Mountains are remarkable because of the character of their northern boundary, the Santa Ynez fault, and also for several other reasons. One of them is the cross-folds already mentioned. These have not been adequately investigated, but several are so conspicuous as to have attracted attention many years ago.[66] One of the most striking, a syncline, is in plain view from the highway across San Marcos Pass. It is a steep-sided syncline, which strikes across the range at an angle of about 40 degrees to its axial trend. A cross anticline separates this syncline from another syncline to the east which has brought down Sespe red beds into the axis and north flank of the mountains. These cross-folds strike almost directly toward the town of Santa Barbara. In line with the anticline there is a sharp bend in the strike of the Vaqueros formation (Lower Miocene) where it lies along the south flank of the mountains northwest of Santa Barbara. West of this flexure the Eocene and Sespe beds which make up the south flank of the mountains dip normally southward; east of it they are overturned for several miles.

As might be expected, the main axis of the San Rafael uplift is in

[66] H. W. Fairbanks, *op. cit.*, p. 501.

some respects one of the most prominent of all the cross folds of the Santa Ynez Range. Its influence seems to have extended far south of the range and to have caused a doming on all the anticlines between the summit of the mountains and the sea. The apex of the dome on which the Ventura Avenue oil field has been developed lies exactly at the intersection of this old cross-fold—dating from the end of the Cretaceous—and the post-Lower Pleistocene east-west fold known as the Ventura anticline.

Another striking cross-fold or cross-fault is found near Gaviota Pass. As noted previously, this is the point at which the Santa Ynez fault splits into branches. One of them continues along the northern flank of the range of hills nearest the coast, while one cuts across this range and strikes the coast line near the mouth of Allegria Canyon, four miles west of Gaviota Creek. This curious structural feature is clearly not analogous to the cross-folds farther east, since its strike is practically at right angles to theirs. It resembles them, however, in the interesting respect that an intra-upper Miocene breccia is found in its proximity along the coast.

Because of the irregularities introduced by the cross-folding, the Santa Ynez Mountain region richly deserves detailed study, but thus far only a few isolated parts of it have been carefully investigated.

CHAPTER VII

VENTURA BASIN

The present Ventura Basin (Fig. 36) is a small part of the crescent-shaped embayment lying to the east and south of the positive area (San Rafael uplift) that came into existence as a result of post-Cretaceous folding. The western end of the southern arm of the embayment is narrow, and is here called the Santa Barbara strait. It lay approximately in the position of the present Santa Barbara Channel. The northern part of the eastern arm has now become converted into high, rugged mountains, so little known geologically that its earlier history as part of the (ancestral) Ventura Basin has not until recently been recognized.

STRATIGRAPHY (FIG. 37)

During the long time from the end of the Jurassic to the end of the Miocene the strata deposited in Ventura Basin (restricted) were not vastly different from those already described from the west end of the Santa Ynez Mountains. The Eocene is thicker, the Oligocene (Sespe) more completely nonmarine, and the Miocene more varied in lithology and in thickness, but in other respects the similarity is great between the two areas.

The thickness-changes of the Miocene are particularly interesting, since they show clearly the beginning of the tendency of the old, crescent-shaped embayment to break up into basins and barriers. Thus in the upper course of Big Sespe Creek, though Lower, Middle, and Upper members of the Miocene are all present, the total thickness is only a few thousand feet. Similar thicknesses are found in Ojai Valley and also on South Mountain, with much greater thicknesses in the Piru Creek and Sulphur Mountain areas.

The marine Pliocene of the embayment area is exposed chiefly in and about the modern Ventura Basin. The great thicknesses often mentioned are found exposed only in a narrow belt north of Ventura and the Santa Clara River Valley. The lithology and paleontology of these beds has been described in many publications, and need not be summarized here. It will be sufficient to point out that the maximum thicknesses as measured by many different geologists lie between 15,000 and 20,000 feet, and that foraminiferal work strongly suggests a depth of water of several thousand feet during the deposition of the Lower Pliocene (Repetto) strata. Since the physical characteristics of the strata have been interpreted to mean deposition in

PLATE VIII-A.—Looking north across Big Sespe Creek at Pine Mountain Ridge. Dark Eocene overlies light-colored Miocene above the Big Pine thrust. Upper Eocene strata near at hand.

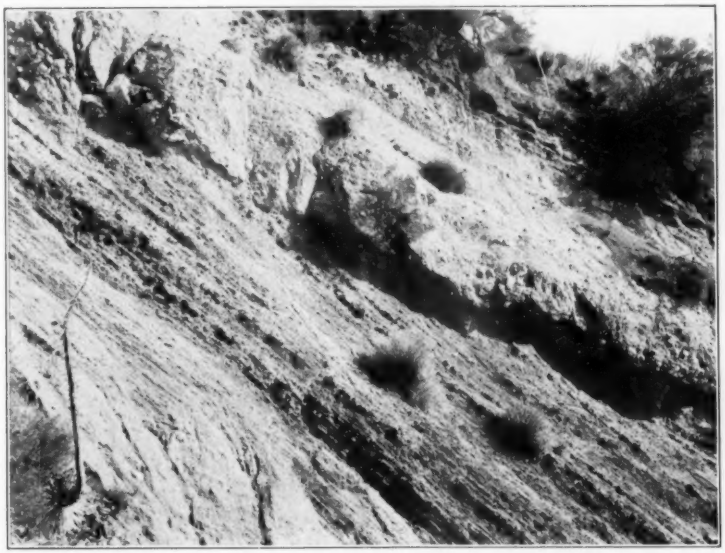


PLATE VIII-B.—Unconformity between Middle Miocene and Middle Eocene, near Sierra Blanca Ridge, San Rafael Mountains. Basal bed on the Miocene has many boulders of Eocene Sierra Blanca limestone. Photo by D. D. Hughes.

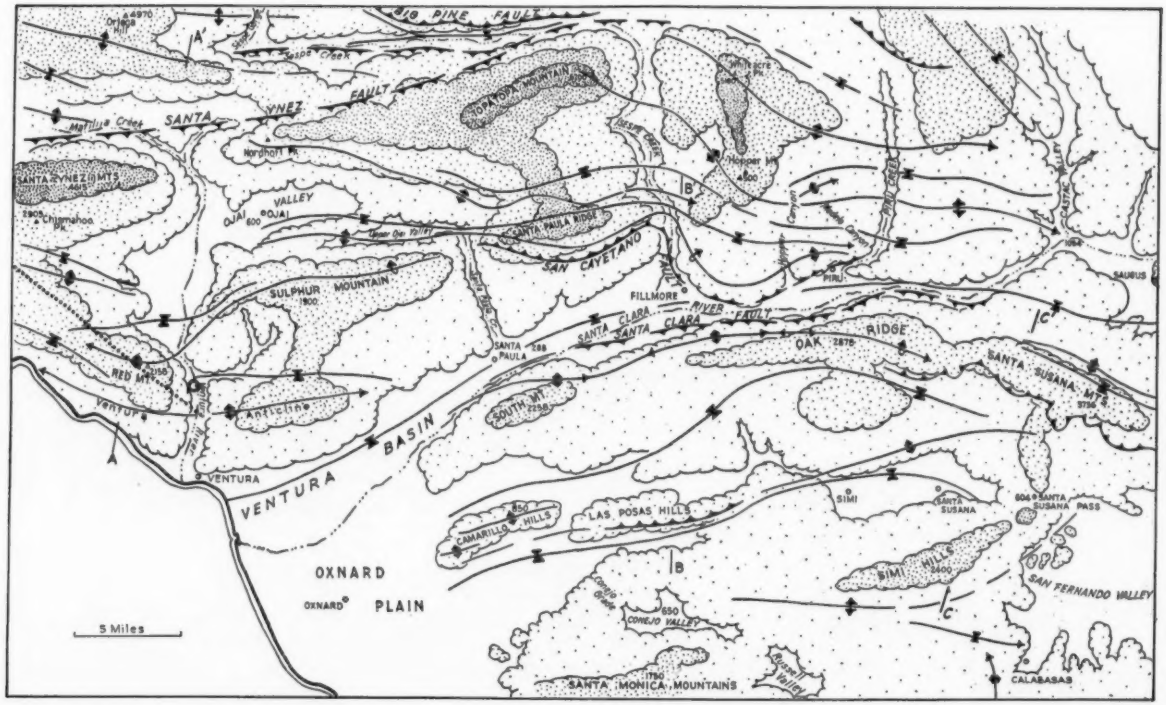


FIG. 36.—Map of Ventura Basin. Symbols as in preceding maps. The line of dots across Red Mountain (west edge of map) is the southeastern continuation of the axis of the San Rafael uplift. The large circle north of the axis of Ventura anticline represents the location of a mass of Upper Miocene intraformational breccia. The more important faults are numbered, as follows: 1, Big Pine fault; 2, Santa Ynez fault; 3, San Cayetano fault; 4, Santa Clara fault; 5, Santa Susana fault; 6, Las Posas fault. The fault shown as normal, northwest of Castac Creek (northeast corner of map), is the Palomas Canyon fault of Clements.

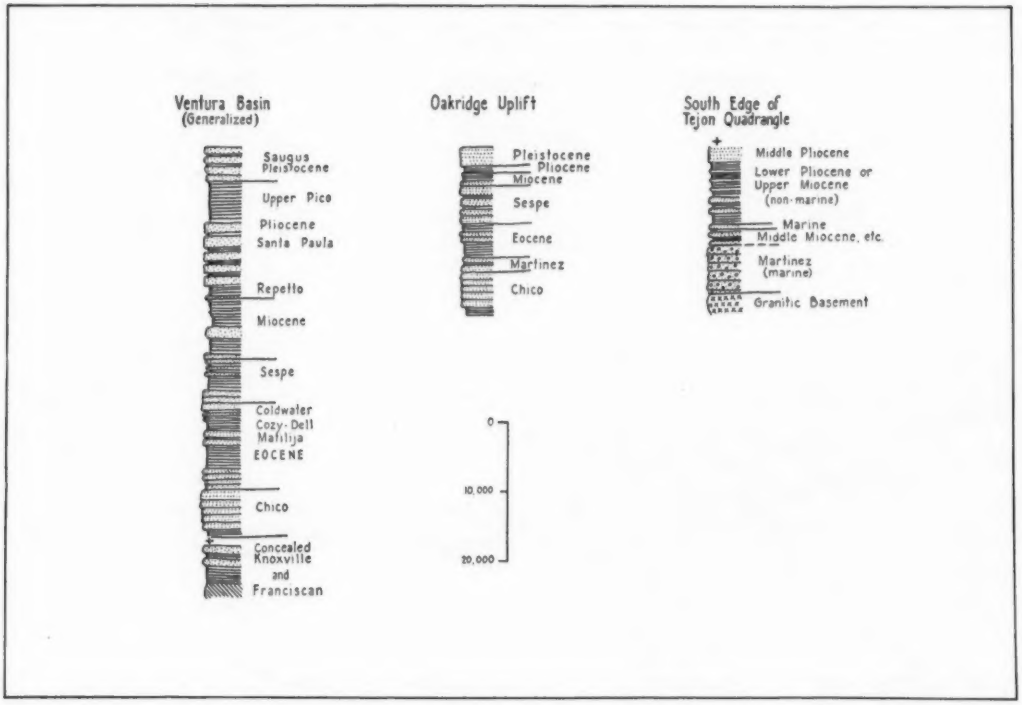


FIG. 37.—Columnar sections of Ventura Basin. Note that the scale is different from that of other charts similar to this.

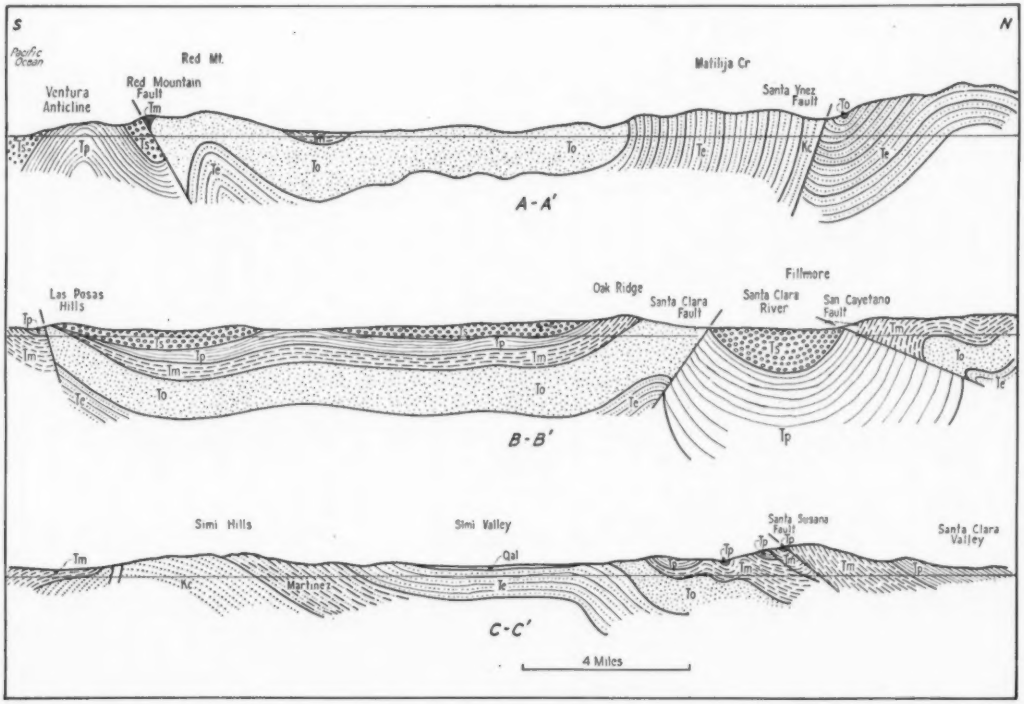


FIG. 38.—Structure sections across Ventura Basin area. Only section *B-B'* crosses Ventura Basin proper, which lies at the south end of *A-A'* and at the north end of *C-C'*. See Figure 35 for lines of sections.

shallow marine water, disagreements of interpretation—in which, strange as it may seem, paleontologists have generally argued for shallow water, geologists for deep—have been numerous and the results indecisive.

The stratigraphy of Upper Pliocene and Lower Pleistocene strata is not yet worked out to the satisfaction of everyone, but the present tendency is to refer a thickness of several thousand feet of the more variable upper part of the post-Miocene folded series to Lower Pleistocene (Saugus, Las Posas, and other formations). These strata are generally marine near the coast, but become nonmarine toward the east; for example, in the Saugus district.

The total thickness of the Sedimentary Blanket is so great that deep drilling has furnished little information as to the character of the older Tertiary and pre-Tertiary formations in the center of the basin. For the purposes of the paleogeographic maps the assumption has been made that the concealed parts of these formations have a thickness that is the mean of the thicknesses exposed to the north and to the east or south. If anyone prefers to assume arbitrarily that the center of the basin was a slowly subsiding area during the Cretaceous and Eocene, there is apparently no way to disprove the assumption, though it is not suggested by any known facts. In any event there is no probability that any assumptions of this kind could succeed in reducing the writers' figure of 68,000 feet to less than 40,000 feet, which in itself is a great thickness for so small a basin.

STRUCTURE (FIG. 38)

The north and south boundaries of the eastern part of the Recent Ventura Basin are made by two faults of much interest. Their development is suggested by Figure 39. At the beginning of the Miocene, the Recent basin began to subside between the areas to the north and south that had previously constituted integral parts of the Ancestral basin. By the end of the Lower Pleistocene the central part of the Recent basin had subsided four to five miles farther than the bounding areas to the north and south. The downward bends of the older strata at the north and south margins of the basin appear poorly adapted to withstand the stresses of the Pasadenan orogeny, and thus may be imagined to have determined the location of the faults.

The San Cayetano thrust has an east-west trend west of Sespe Creek, but makes a big swing to the south immediately east of this stream. The displacement probably reaches a maximum in the area of this southward loop, where it may amount to several miles. The fault can be traced as far east as Piru, beyond which its course is

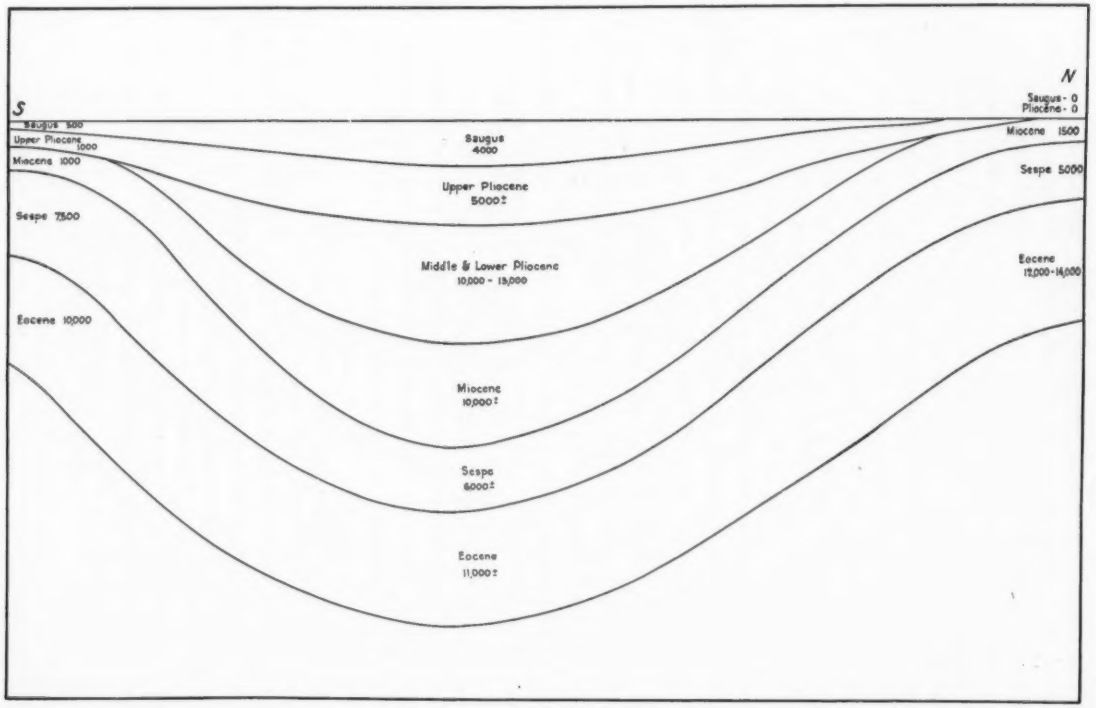


FIG. 39.—Section across Ventura Basin showing conditions before the Middle Pleistocene folding. A comparison with Figure 37, *B-B'*, shows that thrust faults developed at the places where the evolution of the basin had caused the appearance of strong initial bends in the strata belonging to the older Tertiary.

uncertain. The Santa Clara fault can also be traced eastward to about the longitude of Piru, where it seems to die out. The Oak Ridge anticline to the south of the fault continues farther east but in this part of its course it is thrust toward the south, on the Santa Susana fault. In a sense, then, the eastward prolongations of both San Cayetano and Santa Clara faults lose the east-west trend that characterizes them farther west, and are deflected toward the southeast. The deflections are in such direction and amount as to make these structural features parallel with the faults and fault-blocks near Saugus and farther northwest.

It is interesting to notice that the southeast swing of the San Cayetano and Santa Clara faults takes place to the north of the Simi Hills, which likewise have a trend that is out of harmony with the normal trend in the Transverse Ranges, being northeast-southwest. A study of the paleogeography of this area shows that the apparently anomalous trends of these structures are due to the fact that they follow the margin of the apex of the old Santa Barbara embayment. A similar progressive change in strike will be noted later along the north and east sides of the Los Angeles Basin, which occupies the apical part of the Capistrano embayment.

Another curious phenomenon of the eastern half of the Ventura Basin is the symmetrical arrangement of thrust-faults, which occur in pairs. Thus at the north the Nacimiento and Big Pine faults dip under Pine Mountain ridge from opposite sides. The Santa Ynez and San Cayetano faults have a similar relation to Topatopa Mountain, and the Santa Clara and Las Posas faults to the Oakridge-Las Posas upland. Remarkable as it is, the symmetry is not persistent either toward the east or west.

The Tertiary history of the Central Geosynclinal area has many striking analogies with that of the Northern area, as exemplified by the Coalinga district. In both, Knoxville strata are restricted to the approximate areas of the Franciscan; the Upper Cretaceous seas transgressed, at least toward the east; strong folding occurred at the end of the Cretaceous; the Middle Eocene witnessed a major transgression; and the subsidence of later epochs continued to be greatest in the parts lying at the end and sides—in each case the side farthest away from Salinia—of the areas uplifted during the post-Cretaceous disturbance. The Ventura Basin thus corresponds in position, in history, and in thickness of sedimentary blanket to the Maricopa Basin. In each case the deepest basin occurs in the part of the embayment lying at the apex of the old Franciscan area and at the landward end of the folded region formed by the post-Cretaceous orogeny.

CHAPTER VIII

ANACAPIA[67]

The Northern and Central Franciscan areas are separated, as already noted, by a median mass, Salinia. South of the Central Franciscan area, in the region of the Southern California shelf, lies a third area of Franciscan rocks, different from those of the other areas in some respects but even more unlike any other rocks known in the West. Between this southern area and the Central basin lies a province generally treated as part of the shelf region, and thus not separated from the part underlain by Franciscan rocks. In order to focus attention upon some of the peculiarities in the stratigraphy, structure, and history of this intermediate area, it is here treated separately under the name Anacapia.[68]

Anacapia forms the southern boundary of the Santa Barbara embayment. It embraces San Miguel, Santa Rosa, Santa Cruz, and Anacapa islands and the western part of the Santa Monica Mountains. The eastern part of these mountains should perhaps be discussed as a part of Mohavia but is here treated as merely an eastern prolongation of Anacapia, which to all intents and purposes it is.

STRATIGRAPHY (FIG. 40)

Basement rock.—The Basement of Anacapia consists of phyllite and schist, age unknown but often considered Triassic. It is exposed in several areas in the eastern Santa Monica Mountains and in one small area on Santa Cruz Island. The last-mentioned exposure is small, and the schist has suffered such intense metamorphism that its original character and its age have been differently interpreted by different geologists. Since it seems not to have any of the distinctive features of the Franciscan, and since its metamorphism may be due to proximity to a granitic intrusion, it may perhaps be best referred

[67] In the preparation of this chapter much use has been made of the following.

W. W. Rand, "Preliminary Report of the Geology of Santa Cruz Island, Santa Barbara County, California," *Report XXVII of the State Mineralogist* (1931), pp. 214–19.

Carl St. J. Bremner, "Geology of Santa Cruz Island," *Santa Barbara Mus. Nat. Hist. Occ. Paper 1* (1932). 33 pages.

———, "Geology of San Miguel Island," *ibid., Occ. Paper 2* (1933). 23 pages.

H. W. Hoots, "Geology of the Eastern Part of the Santa Monica Mountains," *U. S. Geol. Survey Prof. Paper 165-C* (1931), pp. 83–134.

Unpublished reports on Santa Rosa Island by D. B. Seymour and Graham Moody.

[68] This name is derived from that of Anacapa Island, the easternmost of the four Channel Islands that constitute important parts of the province under discussion.

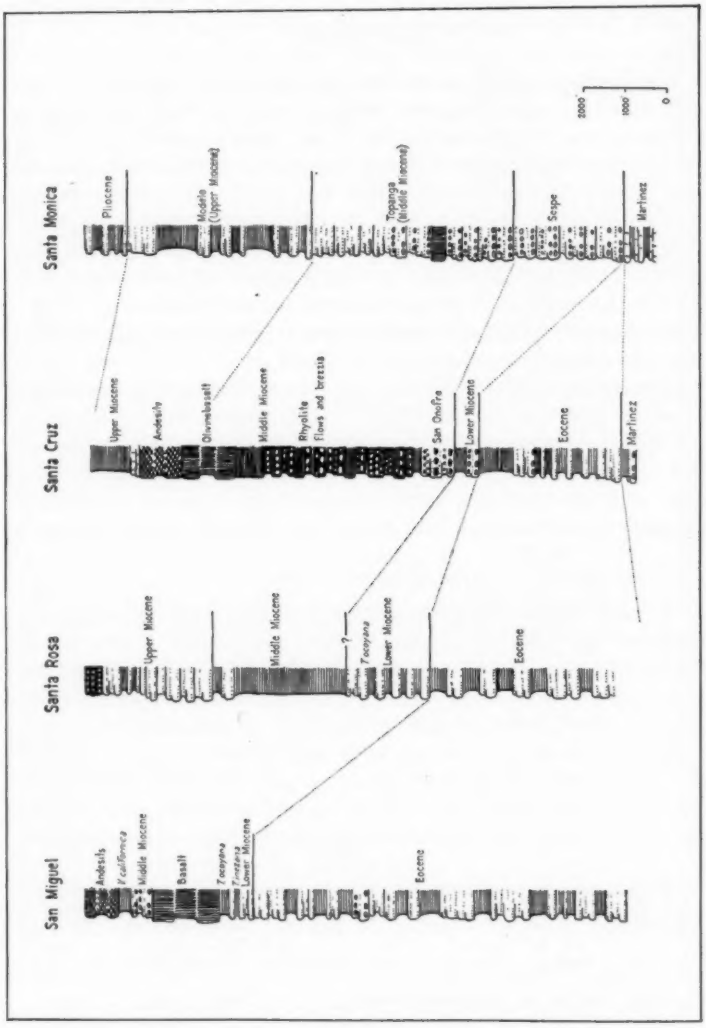


FIG. 40.—Columnar sections of Anacapia. Data for San Miguel and Santa Cruz are from Bremner, for Santa Rosa from Seymour, and for the Santa Monica Mountains, from Hoots.

to the same age as that of the Santa Monica phyllite.[69] The Santa Monica Mountains occurrences have been described by Hoots. Near the granitic intrusion the rock is schistose; farther away it constitutes a broad band of spotted slate and at a distance of a few miles the material is so little altered that the apparent total absence of fossils is surprising. Perhaps it is due to lack of thorough search.

If the Santa Monica slate is not Franciscan, as all students seem to agree, why may it not be correlated with the supposed Paleozoic schists of Salinia and Mohavia? Such a correlation is not impossible, but has never been seriously proposed by geologists familiar with the two types of rock. As a matter of fact, the slate seems to have its nearest analogue in a formation of the Santa Ana Mountains which has yielded a few Triassic fossils. It is here classed as Lower Mesozoic, like the Franciscan. As a probable hypothesis the writers suggest, further, that the Santa Monica slate—and possibly that on Santa Cruz Island as well—was deposited contemporaneously with the Franciscan, but that some unknown condition of basin development or of deposition deprived the former of the peculiar rock assemblage characteristic of the latter. The slates include no radiolarian cherts, they are intruded by granitic rocks and not by basic rocks high in soda, and they lack such minerals as glaucophane and crossite.

The granitic rocks that constitute a part of the Anacapian Basement include diorite, granodiorite, and granite. They seem to agree in all respects with Nevadian granitic rocks of many other districts in California and their age is commonly assumed to be the same (Upper Jurassic, or perhaps lowermost Cretaceous).

Cretaceous.—Lower Cretaceous rocks, though found in the Central Franciscan basin, have not been recognized in the Anacapian district. Upper Cretaceous, including thick marine conglomerates, sandstones and shales, is found in the central part of the Santa Monica Mountains, but not in the single small exposure of pre-Eocene rocks known on the Channel Islands. The Upper Cretaceous strata of the Santa Monica Mountains are associated with Paleocene strata which in general they strongly resemble. Only the fossiliferous Paleocene strata, in fact, including an algal limestone facies,[70] are readily distinguished from the Upper Cretaceous. The Paleocene strata of Santa Cruz Island crop out in one small area. They consist of sandstone and sandy shale, and have yielded some well-preserved fossil mollusks. The exposed thickness is about 350 feet.

[69] Bremner makes this correlation, *op. cit.*, p. 15. Rand describes two granites—one old and altered—cutting the schist, a fact perhaps more consistent with a greater age for the schist.

[70] H. W. Hoots, *op. cit.*, p. 91.

Eocene.—Eocene strata are not known in the Santa Monica Mountains but are found in each of the three larger Channel Islands. The exposed thickness is 3,400 feet on Santa Cruz Island and 9,000 feet on San Miguel Island. The facies is apparently not very different from that on the adjacent mainland.

Oligocene.—Oligocene strata are not definitely known on Anacapia, but may be represented by some post-Eocene pre-Middle Miocene red beds found in the Topanga Canyon area of the Santa Monica Mountains; possibly also by some of the uppermost marine strata, now referred to the Eocene, on Santa Rosa and San Miguel islands.

Miocene.—All three divisions of the Miocene are well represented in the western part of the province, and the two higher divisions farther east as well. Lower Miocene marine strata are found on the three larger Channel Islands and in the westernmost part of the Santa Monica Mountains. They consist of littoral sandstones with a good marine fauna. The thickness on the islands is given as from 600 to 1,600 feet, while that in the western Santa Monica Mountains is stated to be of the order of 5,000 feet.[71] The red beds previously mentioned as possibly Oligocene may also belong to the Lower Miocene. Middle Miocene strata are found nearly everywhere in the Anacapian province. They consist dominantly of coarse marine strata with minor intercalations of argillaceous and siliceous shale. Basic intrusives and flows are associated with the sedimentary strata in all parts of the province. On Santa Cruz Island and at a few localities along the coast of the mainland the lower part of the Middle Miocene includes lenses of San Onofre breccia. The island occurrence is of particular importance because it lies immediately under a foraminiferal shale with a lower Middle Miocene fauna,[72] and thus seems to prove definitely that a near-by area of Franciscan rocks was strongly uplifted near the beginning of the Middle Miocene. The point will be discussed at greater length in the account of the Los Angeles Basin.

Upper Miocene strata are also widespread, and are lithologically variable. In some localities they are conglomeratic or even agglomeratic, in others sandy, and in some are composed chiefly of siliceous and diatomaceous shale of Monterey type (Modelo formation).

The strong angular discordance between Middle and Upper Miocene is conspicuous and widespread in the eastern Santa Monica Mountains but has not been noticed farther west. At the end of the Miocene the entire Anacapian province seems to have emerged from

[71] W. Loel and W. H. Corey, "The Vaqueros Formation, Lower Miocene of California," *Univ. California Pub. Geol.*, Vol. 22 (1932), p. 63.

[72] H. L. Driver, oral communication.

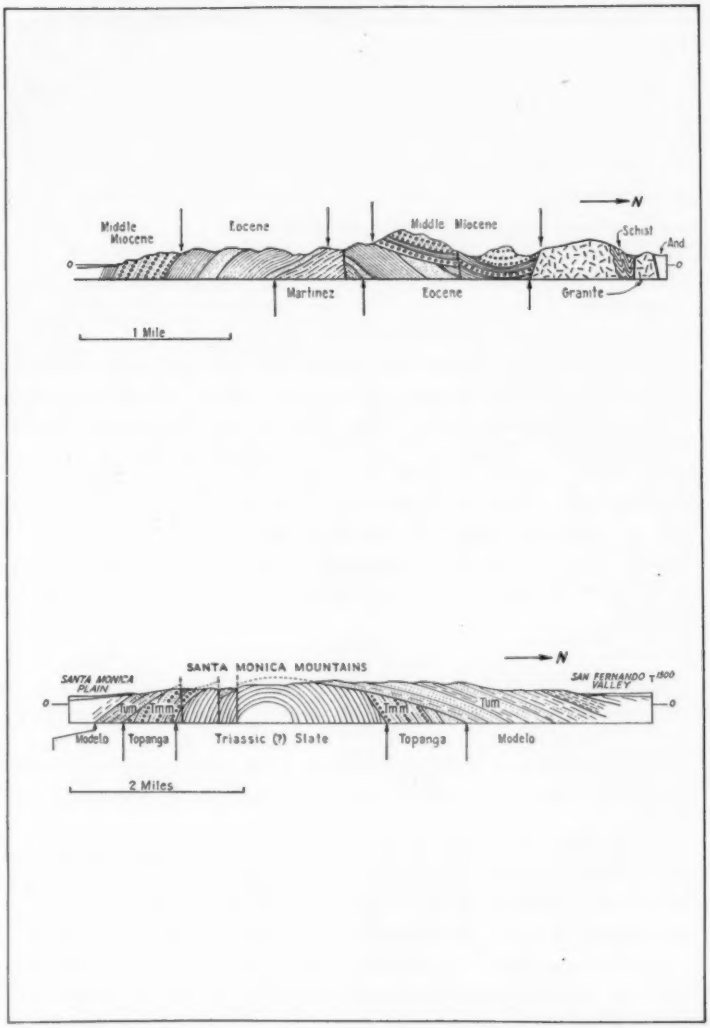


FIG. 41.—Structure sections across Anacapian province. The upper section (Santa Cruz Island) is from Bremner, the lower (Santa Monica Mountains) from Hoots.

the sea, and the parts that can be investigated at present, though locally terraced, seem to have been generally emergent ever since.

STRUCTURE

The Santa Monica Mountain region is essentially a broad, faulted fold with a steep south flank that becomes faulted toward the west. The Channel Island region is also broadly anticlinal, but is crossed obliquely by some smaller folds and by a few important faults. As the structure sections (Fig. 41) show clearly, the folds are in general lower and less steep-sided than many of those found elsewhere in coastal California. The larger faults seem to be nearly vertical, and one of them—the Santa Rosa fault of Santa Rosa Island—has peculiarities thought[73] to demonstrate a horizontal displacement of several miles.

The Anacapian region has obvious points of structural similarity with the San Rafael and Diablo uplifts, and also with many parts of Salinia. Its folds are lower than those of the former provinces, steeper, in general, than those of the latter. It lacks any feature comparable to the Caliente trough, and therefore lacks structures of the type found in the trough. If there is a correspondence between type of structure and character of basement, it seems fitting that Anacapia, with a basement composed partly of slate and partly of granite, should stand structurally somewhere between granitic Salinia and Franciscan San Rafael uplift; at any rate, that is about where it seems to stand.

SUMMARY

Since the recognition of an Anacapian structural province is to some extent an innovation, it seems worth while to summarize the reasons that may be adduced in favor of this procedure.

1. Anacapia is a topographic unit. It is an east-west mountain range with the lower passes—except Cahuenga Pass—flooded by the sea.

2. It forms the southern margin of the Transverse Ranges, and differs fundamentally in structural evolution from the Santa Ynez Mountains, which form their northern boundary, and also from the intermediate area of the Santa Barbara Strait and Ventura Basin.

3. It differs from the areas immediately adjacent to the north and south not only in character of basement rock but also in many points of geologic history.

4. In its history as a positive area it corresponds closely to Salinia: for example, in emergence during Lower Cretaceous, Oligocene, and less completely, during the Pliocene.

[73] Graham Moody, unpublished report.

5. During the Middle Miocene, when the Catalina uplift to the south was strongly emergent, Anacapia was subsiding rapidly.

For these and similar reasons, Anacapia is interpreted as an area the positive character of which dates back to the Lower Mesozoic. It lay within the old geosynclinal belt, and was presumably an integral part of it, but possessed even at that time a distinctive character. The exact outline of this Lower Mesozoic positive area is not clear, since the northern margin may have been gnawed away during the development of the Santa Barbara embayment, the west end seems to have subsided rapidly during the Eocene, and a central area (near Point Mugu) crumbled and foundered during the Lower Miocene. In spite of these vicissitudes, the positive character of the province still seems to be evident in so many respects as to make desirable its recognition as a distinct province.

CHAPTER IX

SOUTHERN GEOSYNCLINAL BASIN AND THE LOS ANGELES BASIN

Compared to the provinces farther north, the Southern Geosynclinal Basin is little known. The sea covers much the greater part of it and the parts exposed fail to give information on several points about which it would be very desirable to know. The difficulties are increased by the fact that none of the islands belonging to this province—Santa Catalina, San Clemente, San Nicolas or Santa Barbara—has been mapped in much detail. The Palos Verdes Hills, which constitute a land-tied member of this island group, are somewhat better known, and as will appear later both they and the western part of the plain near Los Angeles belong to the province under discussion.

The more important stratigraphic features, so far as now known, may be summarized as in Table V.

TABLE V

STRATIGRAPHY OF SOUTHERN GEOSYNCLINAL BASIN

PLEISTOCENE	Marine terraces on all islands and on Palos Verdes Hills; deposits thin. Older Pleistocene well-known only on Palos Verdes Hills
PLIOCENE	Known only on landward side of Palos Verdes Hills, where it consists of thin glauconitic silts of Lower Pliocene (Repetto) age
UPPER MIOCENE	Diatomaceous and siliceous rocks with interbedded volcanic ash, andesitic agglomerate, *et cetera*
MIDDLE MIOCENE	Similar but more cherty, with basaltic and rhyolitic volcanic flows, breccias, *et cetera*
LOWER MIOCENE	Not recognized
OLIGOCENE	Not recognized
EOCENE	Sandstone and shale on San Nicolas Island; about 5,000 feet exposed
CRETACEOUS	Not recognized
BASEMENT	Franciscan schist; large areas exposed on Santa Catalina Island and small ones in Palos Verdes Hills

With reference to this table, it is important to realize that the data apply definitely only to a very small part of the whole province; and further, that the small areas exposed are all alike in being mountain tops. If the areas between them could be studied, they might give a very different idea of the stratigraphic and other relations of the province. The only available method of securing information with which to fill out the details of the picture is to consider what is im-

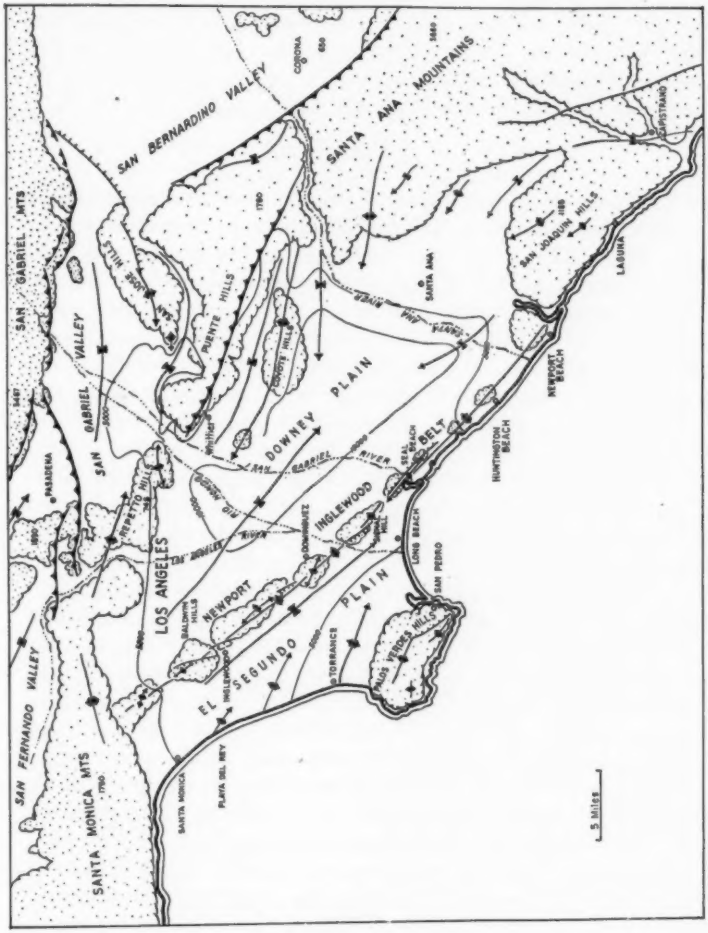


FIG. 42.—Map of Los Angeles Basin. The contours represent depth to the base of the Pliocene; the 5,000-foot contour may be taken as the approximate boundary of the basin.

plied as to conditions farther south and west by what is known of the geology of the district near Los Angeles. How important this knowledge may be for an understanding of the geology of the shelf area may be seen by recalling Woodford's interpretation of the San Onofre breccia.[74] He found clear evidence of the existence of a Middle Tertiary "western land," and inferred many interesting things about its geology. With this example before us we may turn to a study of the geology of the Los Angeles Basin and hills surrounding it (Fig. 42).

LOS ANGELES BASIN

The Santa Monica Mountains, already discussed as the eastern end of Anacapia, form the boundary along a part of the northern edge of the Basin. They are continued toward the east by the hills north of Los Angeles and, east of the Los Angeles River, by the Repetto Hills, at the southeast end of which is an anticlinal ridge upon which the Montebello oil field is located. East of the oil field is a pass through which the Rio Hondo and San Gabriel rivers flow. Structurally this pass is a complex cross syncline lying between the Repetto and Puente Hills. Toward the southeast—beyond the canyon of the Santa Ana River—the Puente Hills rise into the Santa Ana Mountains, a member of the Peninsular Ranges. The western slope of the Santa Ana Mountains is important because it contains a fairly continuous section of Upper Cretaceous and Tertiary strata, all of which dip westward under the eastern edge of the Los Angeles Basin. Toward the south the west flank of the Santa Ana Mountains gives way to the Capistrano syncline, beyond which lies an isolated group of hills with a well-exposed section of Tertiary formations. This group, the San Joaquin Hills, is interesting because, among its other claims to distinction, it is the type locality of the San Onofre breccia, and is the southeast end of an important structural feature, the Newport-Inglewood belt, which will be discussed in some detail on later pages.

The only other marginal group of hills is the Palos Verdes, already mentioned as a land-tied member of the islands of the continental shelf. The Newport-Inglewood structural belt is marked by low hills, however, which constitute a median range across the central part of what is ordinarily considered to be the Los Angeles Basin. From the San Joaquin Hills at the southeast this median belt stretches northwestward, past Huntington Beach, Long Beach, and Inglewood, to merge with the foothills south of the Santa Monica Mountains in the

[74] A. O. Woodford, "The San Onofre Breccia," *Univ. California Pub. Geol.*, Vol. 15 (1925), p. 159.

vicinity of Beverly Hills. The lowland to the west may be called the El Segundo Plain; that to the east, the Downey Plain.

Besides the Los Angeles Basin proper, two or three neighboring "valleys" contain Tertiary strata that throw some light on the history of the area. The more important of these are the San Fernando, San Gabriel, and San Bernardino valleys.

As the home of many geologists during recent years, the Los Angeles district has naturally been the subject of many investigations and of a considerable number of geological publications. Much of the information collected remains in the files of local geologists and of oil companies, but it is to a great extent available as a result of formal and informal meetings and discussions. Only a small part of the total can be summarized here, but an attempt is made to select for presentation those data that bear most directly on the problems of structural evolution of the district and of the old geosynclinal basin to the southwest.

STRATIGRAPHY (FIG. 43)

Basement rock.—In the Palos Verdes Hills the basement rock is Franciscan, belonging to the Catalina Metamorphic Facies of Woodford.[75] Franciscan rocks have also been penetrated in several deep wells drilled in the Torrance and Playa del Rey oil fields and in other parts of the El Segundo Plain. They are not found in the eastern Santa Monica Mountains, where as explained previously the oldest rocks are phyllites of possible Triassic age, which are intruded by granitoid plutonic rocks. In the eastern part of the mountains, north of Hollywood, these granitoid rocks are exposed over considerable areas. In the Verdugo Hills, San Gabriel Mountains, and locally in the San Jose and Puente Hills, the basement rocks are similar granitoid rocks along with gneisses, schists and other metamorphic rocks of many kinds. Except that they are pre-Cretaceous, these rocks are of unknown age. Some of the granites may be of the same age as those in the Santa Monica Mountains, but others may be older, and the associated metamorphic rocks are generally supposed to be Paleozoic or older. Rocks of Franciscan type are entirely absent.

In the Santa Ana Mountains the metamorphic rocks are schist, phyllite, quartzite, and a limestone that has yielded Triassic fossils. The fact that these rocks are different lithologically from the metamorphic rocks of the San Gabriel Mountains and similar to those of the Santa Monica Mountains is the reason for the common assumption that the Santa Monica slate is also Triassic. The Santa Ana

[75] A. O. Woodford, "The Catalina Metamorphic Facies of the Franciscan Series," *Univ. California Pub. Geol.*, Vol. 15, No. 3 (1924), pp. 49-68.

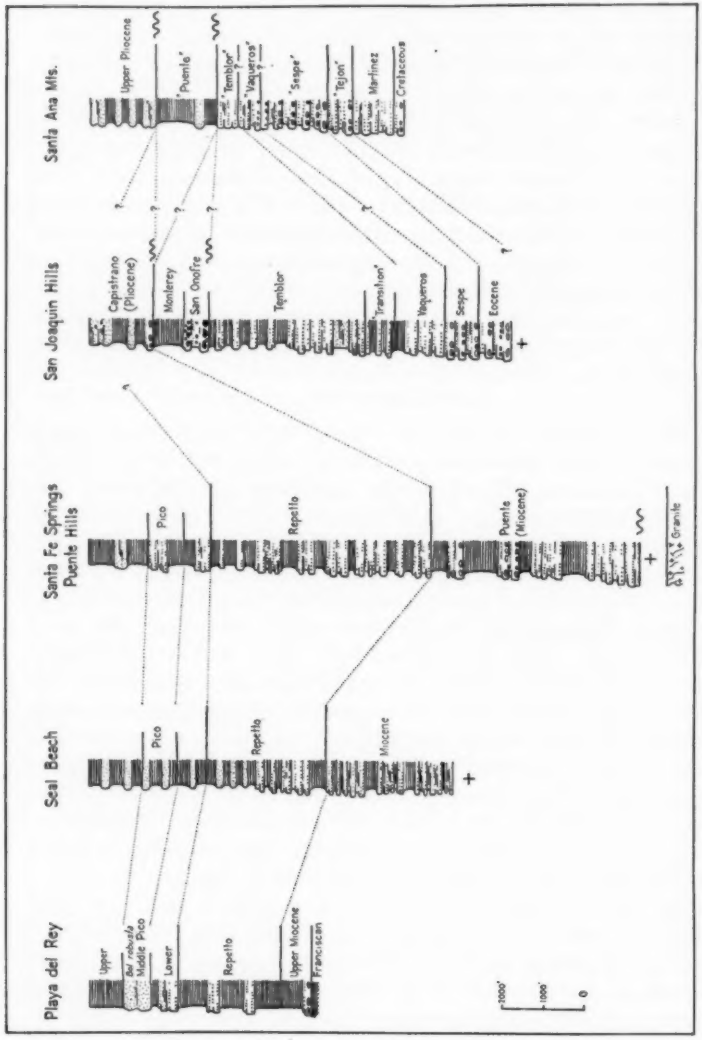


FIG. 43.—Columnar sections to illustrate Los Angeles Basin Tertiary stratigraphy. Note that sections 2 and 3 are incomplete at the base, due to lack of information. The wave symbols indicate unconformities.

metamorphic rocks are intruded by granite similar in character to that of the Santa Monica Mountains. It is obviously post-Triassic in age, and is present as boulders in unconformably overlying Upper Cretaceous strata. It is thus also pre-Chico, and is commonly supposed to be Upper Jurassic, like the similar granite of the Sierra Nevada Mountains.

What is the character of the basement rock of the Downey Plain? The question cannot be answered definitely but as will be explained later most students are inclined to assume the presence of granite or of metamorphic rocks of the Santa Monica type or of both. Further suggestions will be made later in connection with the account of the Newport-Inglewood structural belt.

Beds of Knoxville age have not been recognized south of the east-west line followed by the Santa Ynez Mountains. In view of the fact that this series nowhere occurs in areas of granitic basement, and that the only parts of the Southern Franciscan Basin that can be examined are a few strongly uplifted areas, it is possible that the Knoxville Sea spread over all or part of the area under discussion here but that its deposits were removed by later erosion. By analogy with the occurrence of Knoxville strata in both of the more northerly geosynclinal basins, it seems particularly likely that Knoxville strata either exist now or at least that they formerly existed within the Southern Basin.

Cretaceous.—Upper Cretaceous strata crop out intermittently along the west flank of the Peninsular Range area from Santa Ana Canyon to San Diego. In a deep boring south of San Diego Upper Cretaceous strata were recently penetrated and found to overlie beds like those that yield Triassic fossils farther north. Such facts as this suggest strongly that Cretaceous beds extend westward beyond the present shoreline of the Pacific Ocean near San Diego, and that they underlie at least the eastern part of the Los Angeles Basin farther north. There seems to be no reason to doubt that this formation once covered all of the Los Angeles Basin and of the Southern Geosyncline. The evidence of the San Onofre breccia proves, nevertheless, that it had been removed from considerable areas before Middle Miocene time.

Paleocene.—Paleocene strata are found in the Santa Monica Mountains and on the west and north slopes of the Santa Ana Mountains. They are absent from the northeast margin of the Los Angeles Basin and also from the Palos Verdes Hills. Since they are absent from the Diablo and San Rafael uplift areas, and were apparently never deposited there, it may be argued, by analogy, that the Mar-

tinez Sea also failed to cover the area of the Catalina uplift. The paleogeographic maps, Figures 7 and 8, are drawn on this assumption, but the favorable evidence is indirect and admittedly inconclusive.

Oligocene.—Oligocene time is represented only by undated red beds in the areas east and west of Los Angeles Basin, and is not represented by deposits elsewhere. It is possible that the red beds are all Lower Miocene, since some of them have yielded marine fossils of that age east of Los Angeles. Oligocene deposits may then be entirely absent from this province.

Miocene.—Lower Miocene strata are known east and west of Los Angeles Basin but not along the northern margin or in the southwestern area with Franciscan basement. The available data, including the faunal relations, suggest that their absence from the intermediate area is due to non-deposition. The writers follow Loel and Corey in supposing that a broad peninsular land mass[76]—the Catalina uplift—was in existence in the western part of the Los Angeles Basin and southwest in the shelf area during this time. Strata of Middle Miocene age are more widespread, and may exist in all parts of the district except the landward edge of the old Catalina uplift. In a part of this belt, the evidence of deep drilling shows definitely that they are absent (Fig. 44). The characteristics of the San Onofre breccia demonstrate, furthermore, that the Catalina uplift was high land during at least part of the Middle Miocene. The strong disturbances that occurred at the end of the Middle Miocene are clearly registered by angular discordance in both the Santa Monica and Santa Ana mountains. The folding that occurred at that time is more clearly shown than any other during the entire Tertiary; and it is better shown in the Los Angeles region than anywhere else in Southern California. Yet, curiously, the extent of the Upper Miocene sea in this area is not less than that of the Middle Miocene, but considerably greater. Upper Miocene strata overlap Middle Miocene and lie upon the granite at the north end of the Puente Hills near Pomona and upon Franciscan in the El Segundo Plain southwest of Los Angeles.

The Upper Miocene strata are commonly known as Modelo and Puente formations in this region. They consist largely of siliceous and diatomaceous shale, but have many interbedded members of coarse detritus; for example, in the San Jose Hills and in the western part of Pasadena. In Palos Verdes Hills they even have lenses of schist breccia of San Onofre type. It is probable, also, that some of the higher beds of the San Onofre breccia in the San Joaquin Hills may be of this age.

[76] W. Loel and W. H. Corey, "The Vaqueros Formation, Lower Miocene of California," *Univ. California Pub. Geol.*, Vol. 22 (1932), p. 51 and map 1.

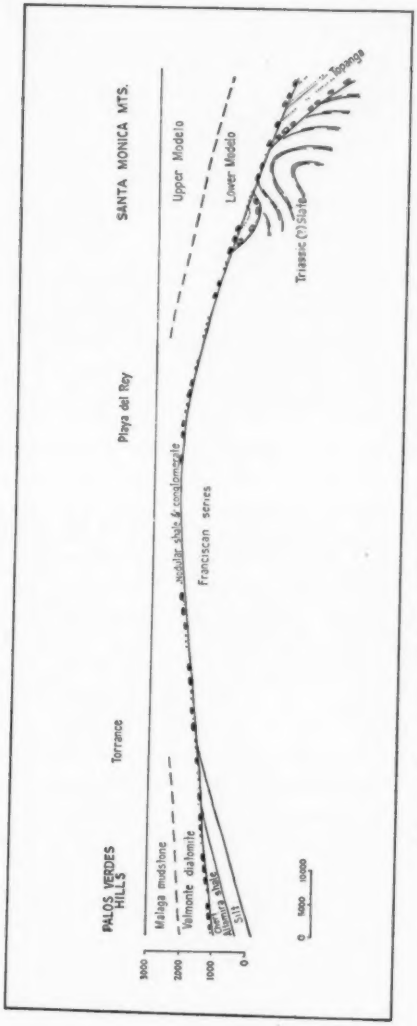


FIG. 44.—Structure section from Palos Verdes Hills to Santa Monica Mountains.

The San Onofre breccia.—That a study of the San Onofre breccia is important in connection with the structural history of Southern California will be evident from the number of times it has been mentioned in the foregoing pages. An understanding of its characteristics and an appreciation of the problems involved in its interpretation are so important for the ensuing discussion that it seems necessary to insert here a discussion of the formation. Most of the available data have been summarized by Woodford,[77] but a few important new facts have since been discovered by Woodford and others. Data of particular value have resulted from an investigation made in the San Joaquin Hills in 1934 by R. W. Burger and H. D. Hobson. Their map, reproduced in simplified form and on a much reduced scale as Figure 45,[78] shows some important facts about the San Onofre breccia that had been missed during earlier investigations.

The breccia is best developed in the San Joaquin Hills and south toward Oceanside. Its thickness in this area amounts locally to 2,600 feet or more, and the largest blocks are 12 feet across. The matrix varies from sandy to earthy, and the detrital fragments consist of blue or green amphibole schists, quartz-amphibole schists, blue-black albite knotted schists, and similar types, all of which occur as autochthonous constituents of the Catalina Metamorphic Facies of the Franciscan. The oldest lenses of the breccia occur in the Temblor, but there are later intercalations in siliceous Monterey shale overlying the Temblor sandstone. The age of these members will be considered more carefully on a later page.

In the Palos Verdes Hills a similar breccia occurs in the Middle Miocene. A coarse and fairly thick lens is found along the west side of the hills south of Malaga Cove where it underlies *Valvulineria californica* shale. Other occurrences are near the small central outcrops of Franciscan rocks on the northeast slope of the hills. Near Point Firmin there are thin intercalations of relatively fine-grained breccia or schist sandstone in Upper Miocene beds.[79]

According to Woodford and Bailey,[80] the breccias of the coastal slope of the western Santa Monica Mountains are lithologically sim-

[77] A. O. Woodford, "The San Onofre Breccia," *Univ. California Pub. Geol.*, Vol. 15 (1925), pp. 159–280.

[78] This map is one of the results of an investigation of the San Joaquin Hills made for The Texas Company and the Continental Oil Company, and is published here by permission of these companies.

[79] W. P. Woodring, M. N. Bramlette, and R. M. Kleinpell, "Miocene Stratigraphy and Paleontology of Palos Verdes Hills, California," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 20, No. 2 (February, 1936), pp. 125–49.

[80] A. O. Woodford and T. L. Bailey, "Northwestern Continuation of the San Onofre Breccia," *Univ. California Pub. Geol.*, Vol. 17 (1928).

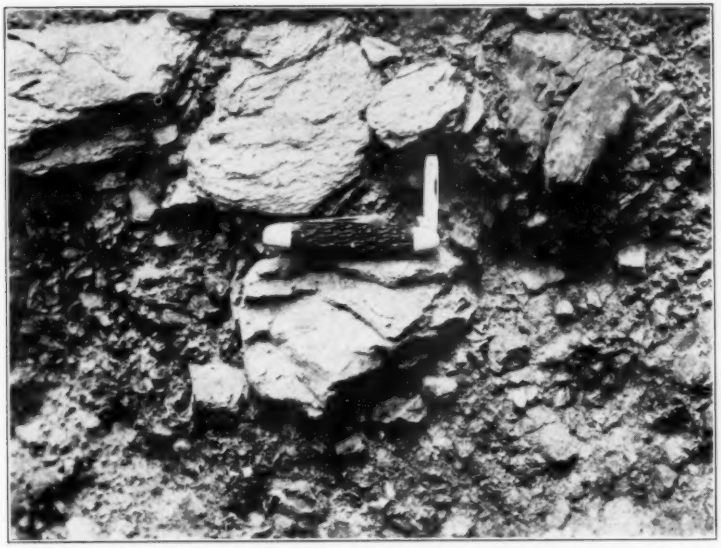


PLATE IX-A.—Outcrop of San Onofre breccia, Middle Miocene, west side of Palos Verdes Hills.

PLATE IX-B.—An exposed oil sand showing overlap relations. On Ramona Boulevard east of Los Angeles River in the city of Los Angeles.

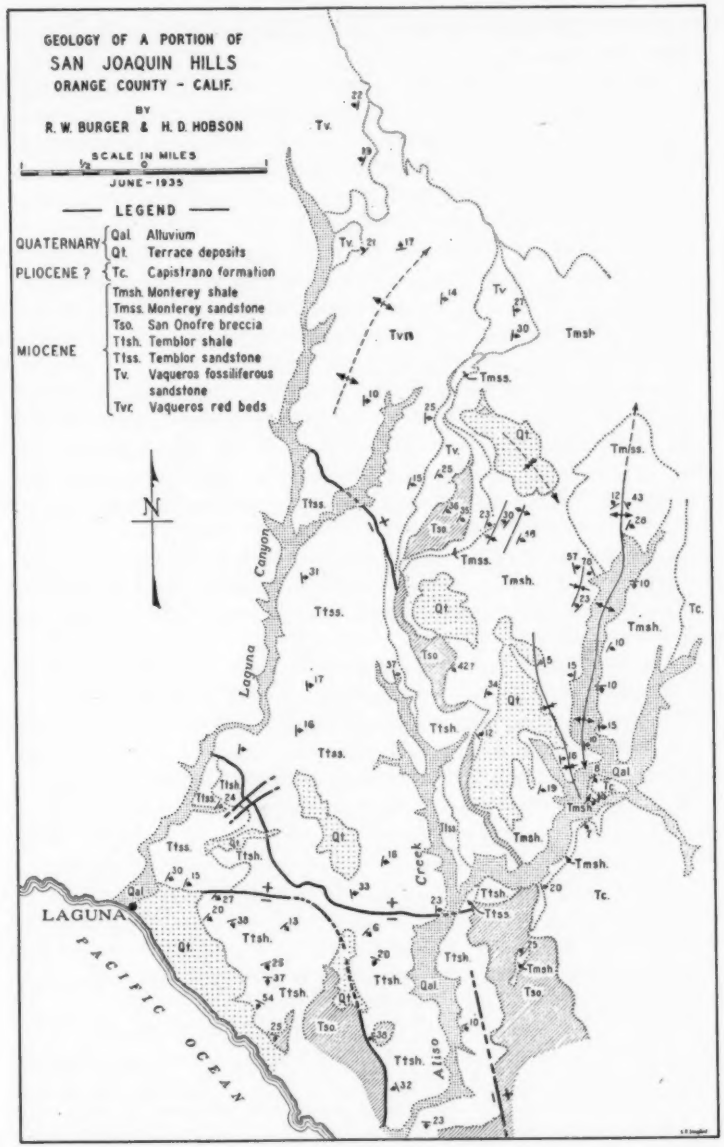


FIG. 45.—Geologic map of part of San Joaquin Hills. Geology by R. W. Burger and H. D. Hobson. See text for discussion.

ilar to those already mentioned. W. H. Corey states[81] that they are of Upper Miocene age.

On Santa Cruz Island the "Temblor" contains a thick member of "coarse unassorted angular conglomerate (San Onofre) grading to finer conglomerate and sandstone" and shale.[82] This occurrence is interesting because it lies beneath a foraminiferal shale carrying a lower Middle Miocene fauna.[83] The Temblor mollusks found associated with the conglomerate are post-Vaqueros; that is, they belong either to the upper Lower Miocene or to the Middle Miocene of the classification used in this study. Here as elsewhere the paleontological data seem to show that the land areas that furnished San Onofre detritus to coastal Southern California were above sea-level by the end of Lower Miocene or very shortly thereafter.

In addition to the stratigraphic conditions, the structural features of the area studied by Burger and Hobson deserve consideration.

The Vaqueros and Temblor members of the Miocene, and red beds ("Tvr") that may be either Miocene or Oligocene, occupy the western part of the area mapped and are cut by some large faults, two of which have an easterly trend and die out at the base of the long, n[illegible]-south strip of San Onofre breccia. The breccia is overlain, appar[illegible] with a slight local discordance, by sandstone and siltstone carrying the Middle Miocene foraminiferal fauna of the *Valvulineria californica* zone.

The implications of these conditions are obvious. The fossils of the Temblor are not older than the upper half of the Lower Miocene, and thus the faulting cannot have taken place much before the end of the Lower Miocene. A short period must be allowed for the reduction to a plain of the irregular surface caused by the faulting. As soon as this planation was completed, the San Onofre breccia may have been deposited. Its age can hardly be greater than that of the button bed; that is, basal Middle Miocene. Unless the apparent discordance between San Onofre and overlying beds is illusory, furthermore, it is also hard to put the San Onofre later than lower Middle Miocene, since the overlying siltstone fauna is referred to the lower part of the *Valvulineria californica* zone, and may even belong to the upper part of the Gould shale (middle Middle Miocene).[84]

This faulting episode which is thus dated with more accuracy than is usual in the case of old faults, is important for several reasons.

[81] "Age and Correlation of Schist-Bearing Clastics, Venice and Del Rey Fields, California," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 20, No. 2 (February, 1936), p. 154.

[82] C. St. J. Bremner, "Geology of Santa Cruz Island," *Santa Barbara Nat. Hist. Mus. Occ. Paper 1* (1932), p. 14.

[83] H. L. Driver, oral communication.

[84] Boris Laiming, oral communication.

First, the date of the faulting is very close to the beginning of the widespread Middle Miocene transgression—thus stimulating speculation as to a causal relation between faulting and transgressions; second, the date is that of the most violent and widespread outbreak of vulcanism in California during the Tertiary; third, the coincidence in date between faulting and breccia deposition suggests that faulting in the region now offshore from Laguna may have had something to do with generating the high rugged lands that are needed to account for the character of the breccia.[85]

That land areas of this kind lay to the west or southwest of coastal Southern California has been clearly demonstrated by Woodford. The detritus of the San Onofre breccia came from an area underlain by the Catalina Metamorphic Facies. Such an area existed, and still exists, in the shelf region south and southwest of the Los Angeles district but not in any other region near enough to furnish coarse detritus to this district. It must therefore be concluded that the Catalina uplift was emergent during Middle Miocene. Woodford sums up as follows concerning this land and the processes that were taking place upon it.

> [The] peculiarities of the San Onofre facies are due to (1) high relief, (2) aridity, and (3) the ease with which the unusual rocks disintegrated to fine pliable flakes and shreds. Pending further advances in our knowledge of sedimentation, the following conclusions may be hazarded. A steep mountain front made possible extensive landslides and avalanches. The occasional torrential downpours formed with the fine schist shreds a slippery medium in which larger fragments of many sizes moved by stages to often distant resting places. Sometimes such a flow swept into the quiet neighboring inland sea, whose waters washed away the finest material, but were often unable to round the edges of the blocks and schistose slabs.[86]

The Catalina uplift was thus emergent during the Middle Miocene, but how about the earlier Tertiary? As Woodford observes:[87]

> The only possible general conclusion is that there is no evidence from the exposed sediments of the existence of a western land mass previous to Temblor time, but it may nevertheless have existed, and that it is especially likely to have been present immediately preceding the Temblor.

As already suggested, the San Onofre breccia has many analogies with the Big Blue of the Coalinga district, which is also Middle Mio-

[85] That some of the faults in the San Joaquin Hills and also in the Santa Monica Mountains are old had been suspected previously because they are followed by basalt dikes. Some doubt persisted, however, since it was not possible to prove that the basalt, though similar to known Miocene basalts, was actually Miocene in age. Now that Miocene faults are known to exist in one of these areas, the probability that some of the others are also Miocene seems definitely better.

[86] A. O. Woodford, *op. cit.*, p. 243.

[87] A. O. Wooford, *op. cit.*, p. 225.

cene in age. The Big Blue was derived from the Franciscan area of the Diablo uplift, which was covered by sediments during the Upper Cretaceous, folded and uplifted at the beginning of the Tertiary, and broadly denuded of its cover by the Middle Miocene. In the San Rafael district there are also conglomerates composed largely of Franciscan detritus. Most of them are found in the Sespe but some of those in the Lompoc district are basal Middle Miocene. They were derived from the Franciscan mass of the San Rafael uplift, which was blanketed with Cretaceous sediments, upfolded at the end of the Cretaceous and stripped of sediments locally as early as Middle Eocene (Sierra Blanca limestone time). These analogies suggest that the Catalina uplift may also have been blanketed with Cretaceous sediments—as the conditions east and southeast of the Los Angeles Basin also imply—and that its first emergence as a land area must have been earlier than Middle Miocene, and may have been as early as the post-Cretaceous folding episode that led to the emergence of the more northerly areas of uplift.

Pliocene and Lower Pleistocene.—Though they underlie many of the low hills about the margin of the Los Angeles Basin and even in the city of Los Angeles, the soft sands and silts of the Pliocene and Lower Pleistocene are not conspicuously exposed in many places. Arnold studied the Pleistocene fossil beds in cliffs and other exposures near San Pedro and described two formations, Upper and Lower San Pedro, separated by a prominent unconformity. His Lower San Pedro beds and their correlatives constitute the Lower Pleistocene of the present discussion, and include the Lomita, Timms Point, San Pedro and other formations of different authors. The pre-Pleistocene beds of the succession were at first called Fernando and later Pico. These names suggest correlation with Pliocene strata of the San Fernando and Newhall districts, 30 or more miles northwest of Los Angeles.

The detailed stratigraphic studies of the past 15 years have led to a more complex classification, or rather to several of them. Though the same units are generally recognized, the nomenclature has not become fully standardized. In order to clarify the discussion of the following paragraphs, Table VI, containing the classification in use in The Texas Company paleontological laboratory, is presented.

The outcropping Pliocene is so varied in lithology and in paleontology that the correlation of the different outcrops even in the Los Angeles Basin might always have remained uncertain if deep drilling and coring had not revealed the more uniform conditions in the part of the series that fails to outcrop. The problems are not all solved even yet, but the last few years have seen a remarkable amount of progress. Much of the information is still incompletely published, and thus not

readily available. A monographic treatment of the problems of the Los Angeles Basin Pliocene would be a most important contribution to California geology.

Figure 42 shows something of the thickness of the Pliocene-Lower Pleistocene succession by means of isopachs. All of the outcrops are outside of the 5,000-foot isopach, though generally not far from it. The basin itself, as will be shown later, may be fairly adequately de-

TABLE VI

PLIOCENE AND PLEISTOCENE OF LOS ANGELES BASIN

PLEISTOCENE
San Pedro or Santa Barbara beds; silts and sands; shallow-water *Foraminifera*
PLIOCENE
Upper Pico ("Library" beds, "mud-pit" shales, *et cetera*); 1,000 feet
Uvigerina peregrina zone; largely silts and fine sands
Middle Pico (Pico "brown"); 700–1,000 feet in wells; uncommon in outcrop
Bolivina robusta zone; upper part sandy, lower part silty
Lower Pico ("Transition beds"); 350–700 feet
Bulimina subacuminata zone
Repetto (also called Lower Pico at one time); alternating siltstone and sandstone members; contains many of the most prolific oil sands of Los Angeles Basin oil fields; carries the *Plectofrondicularia californica* foraminifer assemblage, which can be divided into numerous subzones. Contact with Upper Miocene is unconformable in some sections, but is generally transitional in wells

fined as the area within this isopach. This fact is important in the present connection. The present Los Angeles Basin is to be thought of as a reduced remnant, constituting the central part of the Pliocene basin. This was a marine embayment, broadly connected with the ocean, and deriving its sedimentary materials in part from uplands close to its borders.[88] As the paleogeographic maps show, furthermore, the Pliocene basin was the apical part of the Tertiary Capistrano embayment, and was located at the landward apex of the Catalina uplift. Its position is thus analogous to that of the Maricopa and Ventura basins, each of which occupied parts of Tertiary embayments at the landward ends of uplifts that came into existence at the end of the Mesozoic era.

In order to illustrate the type of structural problem that confronts geologists in the Los Angeles area, it may be interesting to summarize part of the data and to review some of the theories that have accumulated about one prominent structural feature of the Los Angeles Basin. This feature is known variously as the Newport-Inglewood, or Inglewood, "fault," "fold," "uplift," or "belt."

Many of the most important characteristics of this belt may be seen by consulting the topographic sheets of the United States Geo-

[88] See, for example, E. C. Edwards, "Pliocene Conglomerates of Los Angeles Basin and Their Paleogeographic Significance," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 18, No. 6 (June, 1934), p. 786.

logical Survey, such as the Inglewood, Watts, Compton, Clearwater, Long Beach and Seal Beach quadrangles.

Other details are given in some of the economic reports written about oil fields of this belt.[89] Still other data, along with speculations as to the nature and origin of the belt, may be found in papers by J. E. Eaton, Ferguson and Willis, and Hans Cloos.[90] A brief description

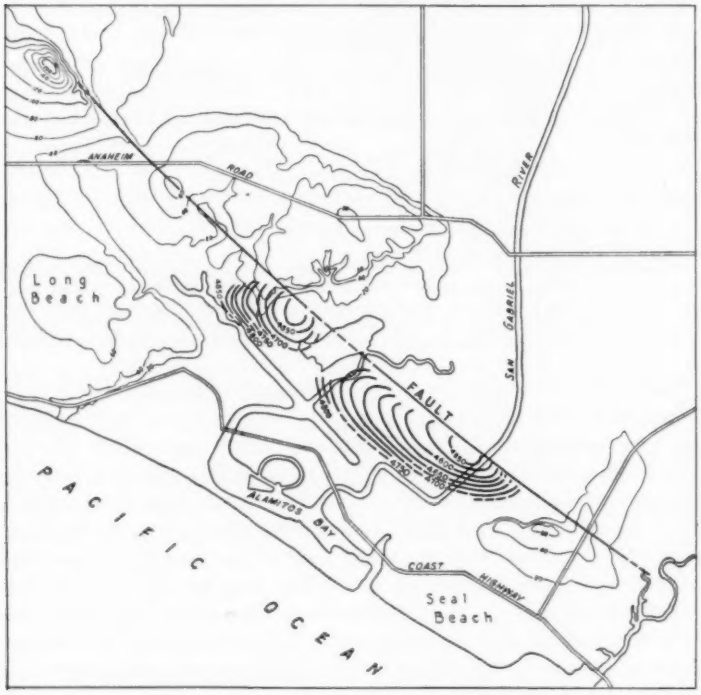


FIG. 46.—Sketch map of Seal Beach oil field and vicinity. Light lines are topographic contours, contour interval 10 feet; heavy lines are structural contours on oil sand, contour interval 50 feet.

[89] See, for example, R. M. Barnes and Glenn H. Bowes, "Seal Beach Oil Field," *Summary of Operations—California Oil Fields*, Vol. 16, No. 2 (1930), pp. 9–31, and several other papers in the same series.

Also, H. S. Gale, "Geology of Huntington Beach Oil Field, California," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 18, No. 3 (March, 1934), pp. 327–42.

[90] J. E. Eaton, "A Contribution to the Geology of Los Angeles Basin, California," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 10, No. 8 (August, 1926), pp. 753–67. (This paper quotes from an earlier paper, published in a trade journal, by the same author.)

R. N. Ferguson and C. G. Willis, "Dynamics of Oil-Field Structure in Southern California," *ibid.*, Vol. 8, No. 5 (September-October, 1924), pp. 576–83.

Hans Cloos, "Bau und Bewegung der Gebirge in Nordamerika, Skandinavien und Mitteleuropa," *Fortschr. Geol. und Pal.* Bd. 7, Heft 21 (1928), p. 287.

with excellent maps and other illustrations may also be found in the Southern California Guidebook of the International Geological Congress, 1933. In the following sketch free use has been made of the publications cited and of many other published and unpublished observations.

The map (Fig. 42) shows the location of the Newport-Inglewood belt, which cuts across the Los Angeles Basin from northwest to southeast. Some of the details that must be fitted into any satisfactory hypothesis as to the nature of the structure are illustrated in the map and structure-section of the Seal Beach-Alamitos oil field (Figs. 46 and 47), which constitutes a small segment near the middle of the belt. As the map shows, it consists of a faulted, twinned dome produced, or at least finally shaped, by folding and faulting in late geological time and by the still more recent erosional activity of a large antecedent stream. The arched surface is offset by a low scarp, which is the surface expression of a small fault. Since both faulting and folding seem to increase in intensity downwards, there is a suggestion that the recent beds took part in only the later stages of diastrophic activity that may have begun considerably earlier.

So far as the data in this map and section show, there is clearly nothing to suggest that the fold is a mere secondary result of faulting, as so many Coast Range folds have occasionally been stated to be. The suggestion is rather that the faulting is minor, the folding relatively major. As in many such cases, however, it may be well to defer judgment until additional facts have been reviewed. Perhaps both fault and fold are mere superficial phenomena related in some way to a structure more profound than either.

That similar arched surfaces cut by similar scarps occur along the whole course of the Newport-Inglewood belt may be readily seen by examining the topographic sheets already cited. Deep drilling has shown that each of the arched areas is a dome, generally faulted. Since the whole belt acts as an efficient groundwater dam, moreover, it has long been recognized as a probable anticline, so far at least as the upper few thousand feet of strata are concerned. The results of deep drilling along the belt and near it on both sides have tended to confirm this hypothesis. The domes and small faults fall into an interesting pattern, especially in the part of the belt northwest of Seal Beach. Both domal axes and faults are arranged *en échelon*, but domal axes are not parallel to faults. The average strike of the faults is more northerly than that of the major structure, the average strike of the domal axes more westerly. Southeast of Seal Beach the minor structures lie approximately parallel to the major one.

Perhaps some justification is needed for the assumption that all

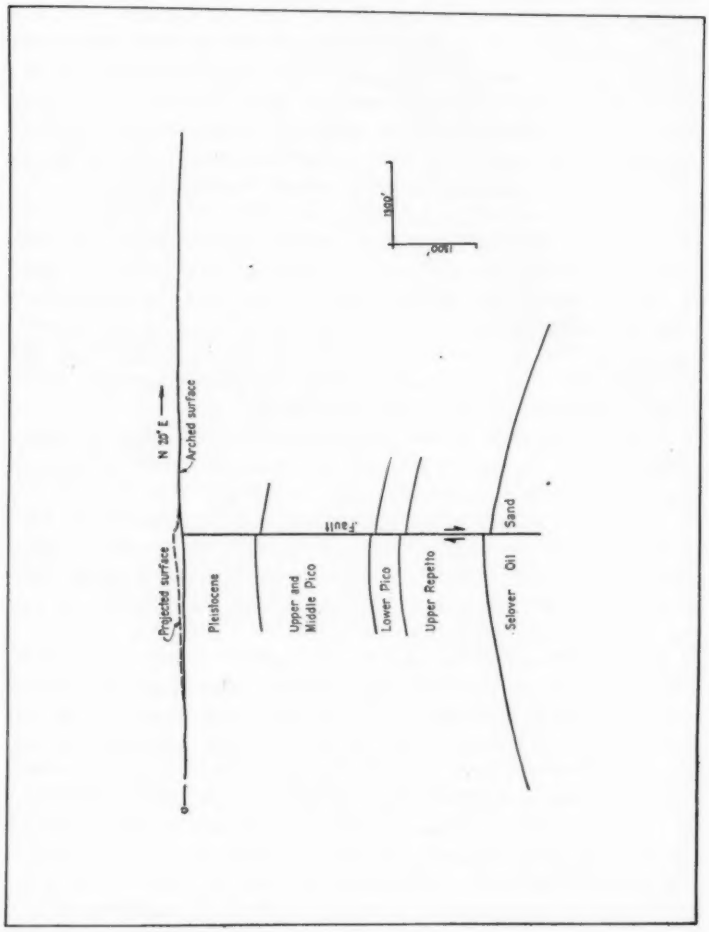


FIG. 47.—North-south structure section across western part of Seal Beach field.

the topographic scarps of the area reflect faults. Proof by drilling has been secured at Seal Beach and Long Beach, and proof from surface observations is available in Baldwin Hills near the northwest end of the belt. In the rest of the area there is little or no evidence for this view, however, except as it may be derived from such considerations as the following. If in an *en échelon* series of scarps, several members are definitely known to reflect faults, there is a good chance that the other similar scarps of the series also reflect faults. Readers who are skeptical of structural interpretations of physiography may feel that this statistical argument helps. If not, they must discount any deductions that may be drawn later from the writers' belief that such scarps as the one north of Dominquez Hills, for example, reflect faults.

The Newport-Inglewood structural belt adds to its other attractions that of serving as epicenter for an occasional earthquake. The Inglewood earthquake of 1921 and the Long Beach earthquake of 1933 are sufficiently recent to come readily to mind. Both quakes were of sufficient intensity to cause damage in the densely populated areas they affected, and for each the epicenter lay below or a short distance southwest of the low hills of the Newport-Inglewood belt. These facts add weight to the hypothesis that the belt is structurally active and important.

But where, exactly, is the Inglewood fault of popular conversation? Is it, as the data in hand suggest, a mere hypothetical structure invented to account for the occurrence of earthquakes and of a line of low, scarped hills trending across the plain of Los Angeles Basin? In spite of the frequency with which this fault has been mentioned and even shown on published maps, its existence remains a hypothesis. Supposed to cross Baldwin Hills obliquely, and to lie along the west foot of the hills farther south, it has not yet been demonstrated to do either. The oblique Baldwin Hills fault is probably no more than a prominent member of the *en échelon* series, as already stated; and the supposed course of the fault farther south—and farther to the north, for that matter—is in the opinion of the writers scarcely entitled to rank even as good hypothesis.

In 1924 appeared two papers[91] which agreed in showing this course for the fault, and also in inferring its existence from the *en échelon* arrangement of the domes. The minor faults were not mentioned, probably because adequate proof of their existence was not available at the time. The papers argued that the *en échelon* folds show the presence of a basement fracture along which shearing stresses have

[91] J. E. Eaton—paper cited in J. E. Eaton, *op. cit.*
Ferguson and Willis, *op. cit.*

operated in geologically recent time. Since these papers appeared, other hypotheses have been invented[92] to account for *en échelon* folds and fractures, but none of them seems to have been applied as yet to the interpretation of those of the Newport-Inglewood belt. Inasmuch as the critical data needed to decide among hypotheses of this type are mostly lacking in any event, there is no present reason for trying to displace the older hypothesis by a modern alternative. It will be more interesting, instead, to assume for the moment the truth of the older hypothesis, and to notice what it seems to imply as to the location of the (hypothetical) basement fracture.

The production of *en échelon* fractures in a tough stratum overlying a brittle one cut by shearing fractures is a well-known phenomenon that has been described and illustrated many times. Fath produced them experimentally in masses of modeling clay.[93] F. Lotze cites and illustrates an interesting case in which both small faults and folds were produced simultaneously and accidentally in wall paper covering the edge of a sagging door.[94] A small-scale geological example, in which minor *en échelon* fractures were produced in a thin bed of tough calcareous material overlying brittle, sheared chert was described and illustrated a few years ago.[95] These cases all suggest that the Newport-Inglewood fault, if it exists, should lie not athwart the uplift or along its margin, but under its axial part.

If relations of this kind are better proved by argument than by example, Figure 48 may be consulted. It is supposed to show that the shearing of the basement would produce stresses in the overlying sedimentary blanket that might be relieved in some places by puckering and in others by the development of short tears; and that the strike of the axes of puckering should be different from that of the tears; and further, that both puckers and tears take place directly above the basement shear.[96]

If the Newport-Inglewood basement fault is assumed to underlie the axial part of the hills, what shall be said of the location of earth-

[92] See, for example, A. Sieberg, "Zur Mechanik tektonischer Vorgänge," *Zeitschrift der Deutschen Geologischen Gesellschaft* (1932), p. 673.

[93] A. E. Fath, "The Origin of the Faults, Anticlines, and Buried 'Granite Ridge' of the Northern Part of the Mid-Continent Oil and Gas Field," *U. S. Geol. Survey Prof. Paper 128-C* (1920), Pl. XIII.

[94] F. Lotze, "Über einige Faltungsprobleme," *Nachr. Ges. Wiss. Göttingen, Math.-Phys. Kl.* (1931), p. 25.

[95] R. D. Reed, "Small *En Échelon* Fractures in Santa Barbara County, California," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 14, No. 3 (March, 1930), p. 320.

[96] A similar interpretation of these features has been given by J. E. Eaton, "Long Beach, California, Earthquake of March 10, 1933," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 17, No. 6 (June, 1933), p. 732.

quake epicenters south and west of the hills? This apparent anomaly will be discussed later, after attention has been given to the relation of the Inglewood belt to the structure of adjacent areas.

Many faults cut the Eocene (?) to Pliocene strata of the San Joaquin Hills, but the one most likely to be the southeastward continuation of the Newport-Inglewood belt lies for the most part offshore. A study of the geology of the hills has nevertheless revealed one feature of interest in connection with it. This is the occurrence in the lower Middle Miocene of the great lenticular mass of San Onofre

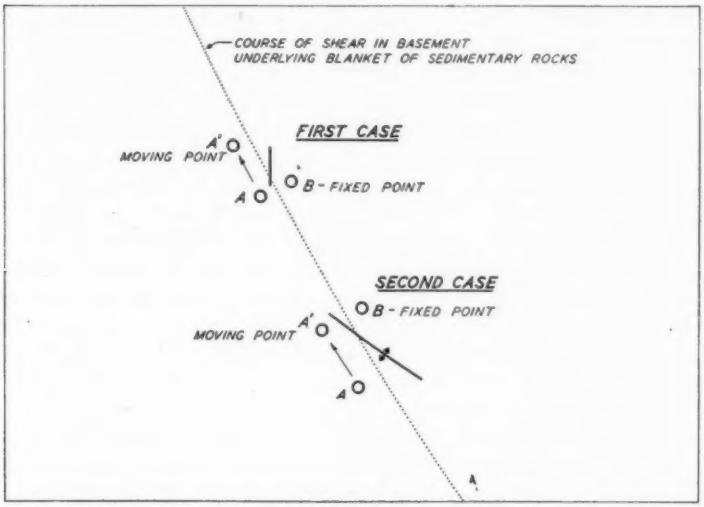


FIG. 48.—Diagram to show possible puckers and tears developed in a continuous blanket of sedimentary rocks resting upon a sheared basement. In the first case, when the distance AB increases to $A'B$, a tear results; in the second case, when AB is shortened to $A'B$, a pucker results.

breccia discussed on earlier pages of this chapter. The importance of this breccia for present purposes lies in the suggestion it gives that the southeastern continuation of the Newport-Inglewood structural belt has been a locus of important movements since the Middle Miocene.

Turning now to the northwestward continuation of the structural belt, we notice that it is not represented either as a fault or fold in the well-exposed rocks of the Santa Monica Mountains. At the south edge of the mountains the low hills of the Newport-Inglewood belt simply merge with the other foothills. The structures of the mountains strike in general east-west, and show very little effect of any diastrophic

events that may have occurred along the belt farther south. This fact serves as a warning against assuming that the belt overlies a fault of great lateral displacement, such as the San Andreas fault is generally supposed to be. Incipient shearing of the kind tentatively inferred above is no doubt a possibility, but great lateral displacement could be accounted for only with the aid of potent accessory hypotheses.

An examination of the map of the Santa Monica Mountains[97] suggests an idea deserving of consideration in connection with the problem of the nature and origin of the Newport-Inglewood structural belt. This idea is based on the observation that the belt is nearly in line with the most important basement contact in the mountains, that between the granite of the eastern end and the supposed Triassic slate that forms the basement in most places farther west. Perhaps the Newport-Inglewood belt marks the boundary between granitic and metamorphic basement along its entire course. That such a boundary might well be followed by an important line of faulting will be evident from the fact that parts of both the Nacimiento and San Andreas fault zones have been shown to follow similar boundaries. A consideration of all that is actually known about the distribution of different kinds of basement in and around the Los Angeles Basin leads to the conclusion that the hypothesis is possible and that it accounts for all the facts, but that it is not demonstrated by them. It has been used as a basis for our paleogeographic maps, but with the realization that it may be demolished by future discoveries in the deep central part of the basin.

If this hypothesis is adopted, the conclusion follows that the Newport-Inglewood anticline follows a basement boundary of the kind that has elsewhere been the locus of important movements during the Tertiary and perhaps longer. The surface anticline may thus be considered to overlie a basement fault. Pursuing the hypothesis farther, we may even infer the direction and degree of dip of this hypothetical fault. On these problems there are, in fact, two types of evidence, both, of course, delightfully speculative. First, if the fault is correctly inferred to be a fracture along a boundary which is a southward continuation of the slate-granite boundary of the Santa Monica Mountains, it may be expected to dip in the same direction as that contact, which is southwest. Second, the seismologic evidence suggests the same conclusion since, as previously noted, the epicenter of the Long Beach earthquake was determined as lying a short distance to the southwest of the surface manifestation of the structural belt.

[97] H. W. Hoots, *op. cit.*, Pl. 1.

If the focus was at a depth of approximately ten miles, moreover, as is considered seismologically possible, the dip of the fault plane may be computed as approximately 75 degrees.

By way of summary, and of returning to earth from the speculative flight of the preceding paragraph, it may be said that in the blanket of Upper Miocene and later strata the Newport-Inglewood structure is a domed, slightly faulted anticline; at a depth of several thousand feet it may be a granite-Franciscan contact that has been a locus of movement since the Middle Miocene and perhaps much longer. The more recent disturbances may have involved a slight shearing tendency which puckered the strata into small domes and fractured them with minor *en échelon* faults. The belt separates the western part of the Los Angeles Basin, which is topographically the El Segundo Plain and structurally a part of the Catalina uplift, from the eastern part, which is topographically the Downey Plain and structurally the landward apex of the Capistrano Tertiary embayment.

The other structural features of the Los Angeles district must be passed over hurriedly. Northeast of the Downey Plain lies a series of folds, also more or less clearly reflected in the topography: Montebello, Santa Fe Springs, and West Coyote anticlines, and others farther east. In the Santa Ana foothills and San Joaquin Hills are numerous folds and faults, the strike of which is more nearly north-south. The chief characteristics of these structures may be learned from an inspection of Figure 42.

The depth of the basement beneath the Downey Plain constitutes a problem about which many and divergent ideas have been expressed. On the basis of a geophysical investigation, Buwalda and Gutenberg have recently expressed the view[98] that it lies at a depth in excess of 40,000 feet. If so, the post-Jurassic pre-Miocene strata that are missing from the western part of the basin must be well represented in the area east of the Newport-Inglewood belt. Since there are no facts definitely opposed to this hypothesis, it has been adopted in drawing the accompanying paleogeographic maps and sections.

STRUCTURAL HISTORY

In Upper Cretaceous time the Los Angeles area is thought to have lain near the margin of the sea, but to have been completely flooded and to have become blanketed with sediments from 2,500 to 5,000 feet or more thick. There was a period of folding at the end but the accompanying uplift must have been small, since Paleocene strata

[98] J. P. Buwalda and Beno Gutenberg, paper read at 1935 meeting of Cordilleran Section of Geological Society of America, Stanford University, April, 1935.

are found both in the Santa Monica and Santa Ana mountains. There is, however, no reason to suppose that they were ever present in the Franciscan part of the region, which may have been strongly uplifted (Catalina uplift).

Eocene strata are preserved in the Santa Ana Mountains and are presumed to underlie the greater part of the basin. They may once have covered the whole area, perhaps with the exception of the part underlain by Franciscan basement.

The distribution and character of the red beds that furnish the only possible record of Oligocene deposition show that the Oligocene was certainly a period of sea-withdrawal, and perhaps of deep erosion over much of the area. During the Lower Miocene the sea flooded the San Joaquin Hills area and perhaps the deeper eastern part of the basin, but the area farther west was still undergoing erosion. During the Middle Miocene it seems likely that the sea flooded the entire area now occupied by the basin and the surrounding hills. The sedimentary rocks of this stage include thick bodies of sandstone (north edge of Santa Monica Mountains and Pasadena area), the San Onofre breccia (San Joaquin Hills), and siltstone and chert (Palos Verdes Hills). There is also a large amount of intrusive and extrusive volcanic material. The initiation of the Middle Miocene transgression was certainly attended by notable faulting in the San Joaquin Hills area and probably elsewhere. After a subsidence sufficient to allow the accumulation of several thousand feet of varied sediments, a new disturbance set in. The exact nature of the folds made at this time is not known, but one of them may have uplifted all that area west and southwest of the Newport-Inglewood line. Middle Miocene strata are now found north of the axis of the eastern Santa Monica Mountains and south of the axis of the Palos Verdes Hills. In the district between these axes, Upper Miocene strata lie on basement rocks (Fig. 44). In the Santa Monica Mountains, furthermore, the Upper Miocene is strongly discordant on the Middle Miocene.

In the Los Angeles-Pasadena area, both Middle and Upper Miocene strata of generally coarse texture are present in great thickness and the contact between them is difficult to locate. In the Puente Hills, on the other hand, Upper Miocene strata lie locally on pre-Tertiary granite, and the Middle Miocene is known to be represented only in a small area in the southeast corner of the hills near Santa Ana Canyon. An overlap is thus demonstrated for this region and an unconformity is not unlikely. In the Santa Ana foothills, moreover, Upper Miocene lies on the older Miocene (Middle or Lower) with a discordance comparable to that of the Santa Monica Mountains. A

pre-Upper Miocene folding period is thus strongly suggested for a considerable part of the border of the Los Angeles Basin.

The end of the Miocene was marked by a restriction of the sea, with probable folding and uplift of a part of the border area. In the basin itself, however, sedimentation continued with so little interruption that the selection of the exact boundary between Miocene and Pliocene, in deep well cores for example, is a difficult task.

During the Pliocene epoch the sea boundaries shifted several times. At one stage, the Middle Pico *Bolivina robusta* time, there was a regression of marked character northeast of the Newport-Inglewood belt. Though known from numerous wells, strata representing this stage crop out only in one small area in the whole Los Angeles district and that is near Santa Monica, west of Inglewood. This regressive epoch was followed by a time of relatively widespread seas in which clays, silts, and muddy sands accumulated. These were followed by several hundred feet of coarser Lower Pleistocene strata of varied lithology. The main phase of the Pasadenan folding then intervened, to be followed by the deposition of the thin and varied sediments, marine and nonmarine, of the Upper Pleistocene.

The picture that emerges from a consideration of these and other facts is of a long series of uplifts, downwarps, faultings, foldings, with a continual shifting of folding axes and of centers of most rapid sinking. The Los Angeles Basin lies at the meeting place of several geologic provinces; it represents the place of maximum subsidence in an embayment which, like the embayments previously studied, shifted as it developed and was folded in different parts at different times.

CHAPTER X

SUMMARY AND CONCLUSIONS

The structural evolution of Southern California has involved the enactment of a long series of events upon a stage of ever-increasing complexity. The maps—particularly Figures 5 and 15, and Plate 1, or the successive paleogeographic maps, or Figures 2 and 6—show something of the increase in complexity of the stage. The varying movements and processes acting in the same place at different times, are less easy to show graphically. To some extent they become evident from an inspection of the columnar sections, but something else is desirable. Stille, Bubnoff and others have used diagrams for the purpose of displaying graphically the succession of events in different areas. Following their example, the writers offer Figures 49–57.

In these diagrams the vertical columns denote periods of time, the width of the columns representing a rough approximation to the length of each period. Of the horizontal columns, "F" shows where the surface of the area in question lay at any time with respect to sea-level. If the area was above sea-level and was undergoing erosion, the curve runs above the zero line without hachures; if the area was above sea-level but was receiving deposits, the space between the curve and the zero-line is hachured. Great depths of water are indicated by dropping the curve below "1,000′," and placing a plus sign in the downward loop. It scarcely needs to be said that the depths indicated are in most cases guesses without a very substantial foundation.

In the second horizontal column, "Tr," positive and negative transgressions are indicated by arrows, the negative transgressions (regressions) being shown by upward-pointing arrows. In the "Th" column, thicknesses are shown in thousands of feet; thus "IIII" represents 4,000 feet, and "~~IIII~~" represents 5,000 feet. In the column marked "O," the more important orogenic phases are indicated by three types of symbols, a wave symbol (well-authenticated folding episode), a zigzag (well-authenticated faulting episode), and a deformed question mark (inadequately demonstrated or poorly dated orogeny). In column "V," finally, the time of outbreak and something concerning the nature of volcanic activity are indicated; thus "t" stands for tuffs, "a" for andesites, "b" for basalt flows, and so forth.

Diagrams of this kind, even when drawn with dotted lines and question marks in the more doubtful places, probably have a tendency

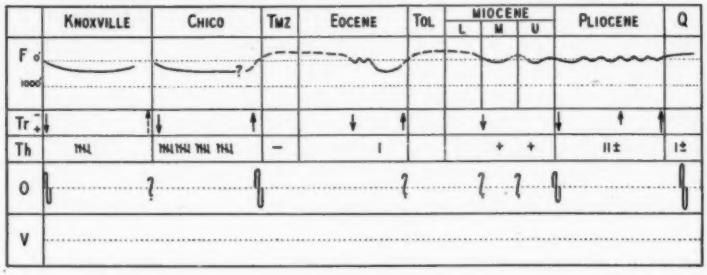


FIG. 49.—Geologic events in Coal Mine Canyon, Coalinga area.

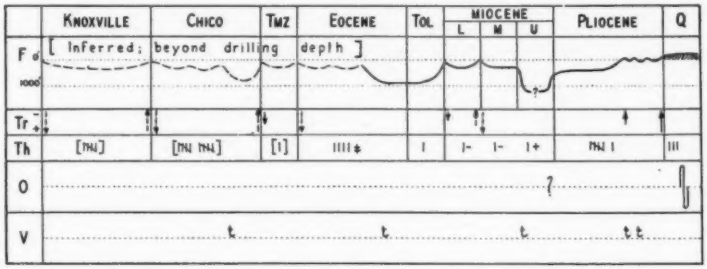


FIG. 50.—Geologic events in Kettleman Hills, Coalinga area.

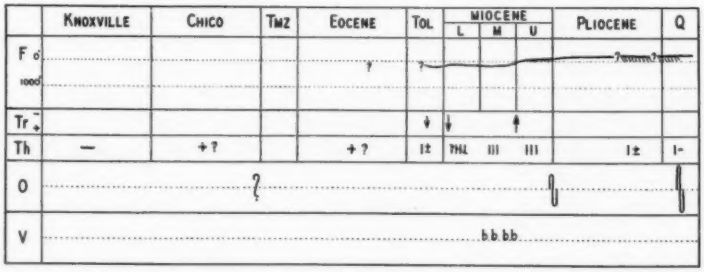


FIG. 51.—Geologic events in Caliente trough.

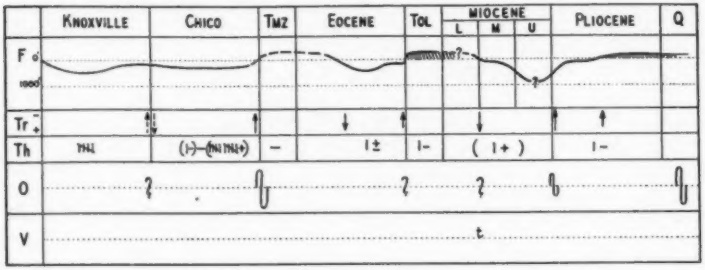


FIG. 52.—Axis of San Rafael uplift.

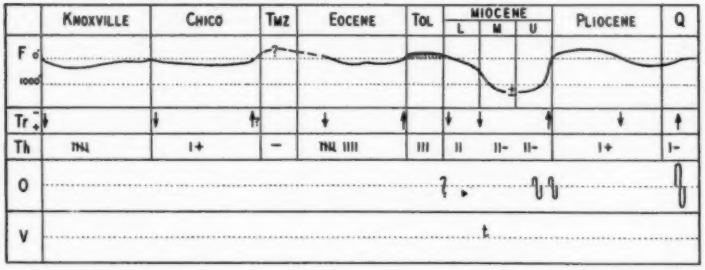


FIG. 53.—Santa Barbara Coast.

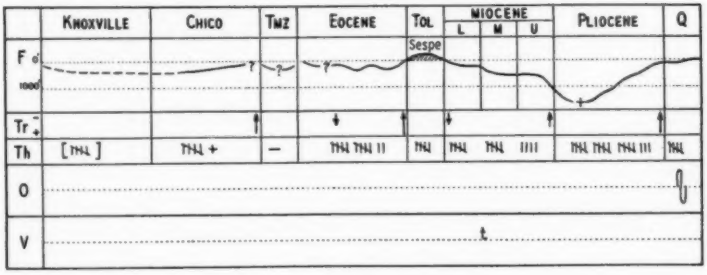


FIG. 54.—Ventura Basin.

to gloss over uncertainties and to present tentative interpretations too positively. They should therefore be considered merely as pictures, and reference should be made to the text for a discussion of the character of the evidence upon which they are based. It would probably be better still if each interested reader could be persuaded to impress the uncertainties upon his mind by personally making one or more similar diagrams from the data found in this volume or elsewhere.

A group of tectonic provinces undergoing incessant changes from the effects of a series of diastrophic events; basin development continuing for ages until a new folding spasm grips the area and leads to uplift of some parts and to greater or less displacement of old basins or even to the initiation of new ones; continual shiftings of sea margins with occasional culminations of sea advance or sea withdrawal; a continual increase of structural complexity, a steadily lessening average area of subsiding basins, and at the last a great and sudden increase in the extent of land area and the average height above sea-level: such is the concept with which one emerges after a tectonic analysis like that carried out in the foregoing pages. What are the conclusions to be drawn from it all?

Structural geologists who read this far will wonder, in particular, where the writers propose to discuss the dynamic problems that bulk so large in most treatises similar to the present one. What is the nature of the forces that from time to time have deformed the crust of coastal California, and what their origin? Were the mountains warped up, thrust up, or elevated in some other way? To all such questions the writers must answer that they do not know. They must state further that in spite of their best efforts they do not yet know as definitely as they would like just what structural events happened from time to time and from place to place in the California province; and they may as well confess that they doubt the advisability of creating mechanical hypotheses, except for mnemonic purposes, until the succession of events to be explained has been well worked out.

The role of mechanics in structural geology has been stressed by many geologists and its importance is too obvious to need discussion. For a preliminary study like the present one, however, its chief use in the opinion of the writers is to furnish a basis for the criteria needed for deducing the time-succession of tectonic events. They use mechanical concepts in determining which side of a stratum was originally top or bottom, or which of two intersecting dikes is the younger; but not, in advance of the most thorough possible historical study, in deciding how a given mountain mass was raised. Even in approaching the end of their work, they can furnish little aid to those of their

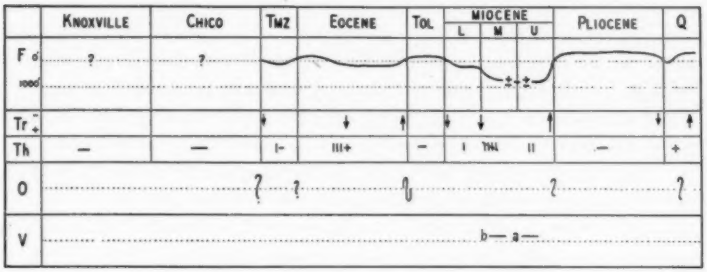


FIG. 55.—Santa Cruz Island.

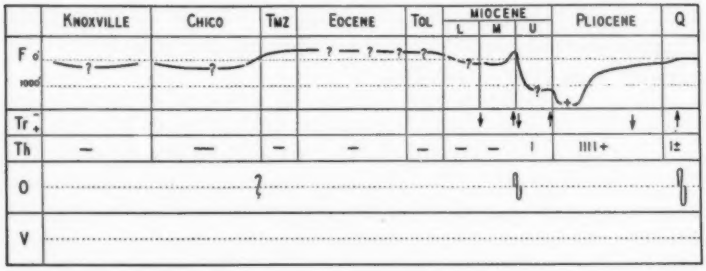


FIG. 56.—West end of Los Angeles Basin.

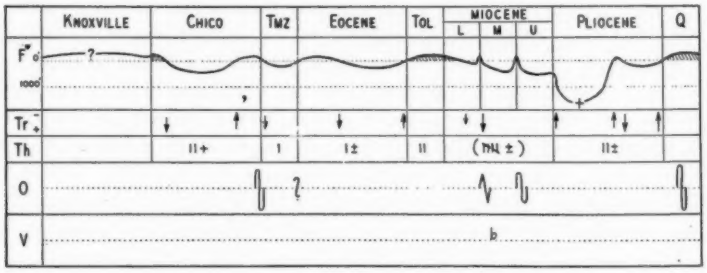


FIG. 57.—East end of Los Angeles Basin.

readers who cannot rest content without knowing what kind of forces were at work in producing the complex series of structures that make Southern California so exciting an area in which to do geological work. About all they can do for such readers at present is to acquaint them with the types of puzzle for which explanations are needed.

Before proceeding to this modest summary of problems and phenomena it may be well to define a few terms that have been used in some of the foregoing pages with meanings possibly different from those assigned to them by some readers.

Orogeny or *orogenesis* is the name applied to structure-transforming movements of episodic character. After a distinctly orogenic period the structure map of such a mobile area as the Coast Ranges should record some striking changes.

Epeirogeny or *epeirogenesis* designates movements of secular character that result in the warping of an area into broad uplifts and depressions, or in slow up-and-down movements of continental scale.

Orogeny is never world-wide in the sense of notably affecting the structure of stable belts as well as of mobile belts. Whether or not it is world-wide in the sense that it simultaneously affects all mobile belts the world over is a problem of much interest and importance on which opinions differ widely. Obviously, if all mobile belts are so affected during even a great orogeny, we are in the presence of a "law" of first-rate importance to all who wish to understand—or explain—tectonic activity. An affirmative view has been taken by Stille,[99] who summarizes at length the evidence from all parts of the world. His conclusions are accepted with some reservations by Bubnoff, Bucher and others, but are rejected or at least considered undemonstrated by some. Many of those who object do so for theoretical reasons, based commonly on undemonstrable beliefs concerning the cloudy mysteries of crustal mechanics. Others hold, with some justice, that the "law" is based on interregional correlations that are not always above suspicion.

Between orogeny and epeirogeny Stille recognizes two transition cases: synepeirogenic and synorogenic movements. The former, though acting during epeirogenic periods, cause orogenic manifestations in such highly mobile materials as salt or magma; the latter, though "epeirogenic" in intensity, act during orogenic periods in areas too stable to be strongly affected by orogenic movements of the intensity of those that happen to be active at the time.

The area discussed in the foregoing pages is too small to throw

[99] H. Stille, *Grundfragen der vergleichenden Tektonik*, Berlin (1924).

much light on problems concerning world movements, but has nevertheless yielded results that may be of interest to those engaged in studying such large problems. In the first place, despite the small size of the area, it consists of provinces differing greatly from one another in mobility. Mohavia, Salinia, and Anacapia are all relatively stable, the latter being least so; compared to them the Northern and Central Franciscan areas are notably mobile, and probably the little known Southern area is so too. Thus, although they are not far apart, it is interesting to notice that the orogenic time-law seems to hold remarkably well for the provinces that are similar to one another in character of basement. Any disturbance that affected the Coalinga region is sure to be definitely recorded, in much the same way, in the Santa Ynez-San Rafael region. As our correlations become more trustworthy the correspondence in history between these and other pairs of like provinces becomes ever more striking. Thus the information available at present enables us to state a local orogenic time-law of our own: so far as the post-Franciscan history of Southern California is concerned, tectonically comparable areas seem to have been similarly affected at all times by orogenic and epeirogenic forces.

If the same geologist were able to study one after another several regions comparable in size and complexity to Southern California, and to work out for each of them a classification into tectonic belts and the sequence of tectonic events for each belt and for the region as a whole, he would then be able to decide whether or not our local orogenic time-law can be generalized. If he found, for example, that the Caribbean-Antillean province and the Malay archipelago were strongly folded and metamorphosed—at least in the more mobile belts—near the end of the Jurassic, and that certain subprovinces began thereafter to subside to great depths; that they were locally invaded by the sea during the Lower Cretaceous and more broadly in the Upper; that they were strongly folded—again in certain belts—at the end of the Cretaceous; and that all through the Tertiary there was a succession of tectonic events comparable, belt for belt, with that elaborated on previous pages; he might eventually come to feel not only that the orogenic time-law is valid for the whole world, but also that Stille's "canon of strand-shiftings" and similar generalizations are understatements rather than exaggerations. If the course of structural evolution has actually varied greatly from place to place, on the other hand, such a study should make the fact obvious.

Since adequate investigation of any such series of large areas by one man is hardly practical, no definite and final conclusion on these fascinating problems is likely to be possible for some time to come.

The writers have made casual studies of the material available to them about certain peri-Alpine districts in Europe and Asia, the Antillean-Caribbean region, and the East Indies, and have been impressed by some of the striking analogies in their history, but have not found the evidence complete enough to lead to definite conclusions. Perhaps geologists more familiar with those or other mobile regions may be able to carry the comparison farther and reach more satisfactory results.

In this connection it may be pointed out that the areas which are called "uplifts" and "embayments" in the foregoing pages and which seem to have originated at the time of the Laramide disturbances near the end of the Cretaceous, have many analogies with the "orogens" and "foredeeps" of some European geologists; and that the Laramide folding, the peculiar two-phase mid-Miocene disturbances, and the Pasadenan folding seem to be the "orogenic" events most likely to be recognizable in other regions tectonically comparable to Southern California. The Middle Eocene and Middle Miocene transgressions were also widespread in California and might be expected to be similarly noteworthy in any other province with which Southern California might be comparable. In comparing the California succession of tectonic events with those of other countries, due weight must of course be given to the probability that the Oligocene of other regions represents not only the Oligocene but also much of the Lower Miocene of California.

The Middle Miocene transgression, initiated by faulting with rhyolitic and basaltic outbreaks and followed by folding with andesites, is particularly worthy of study. With it in mind as an example, one is led to ask if the history of vulcanism may also furnish a succession of events more or less the same in widely separated parts of the world. The question has been raised before, at least by implication, and has commonly been answered in the negative without much hesitation by those who specialize in the occurrence of igneous rocks. Volcanoes now active erupt rocks of almost every type, we are told, and there is not much likelihood that in this respect the past has been different from the present.

The statement is no doubt true, but does not fully answer the question. It seems to ignore the fact that in the past as in the present the crust of the earth has been divided into tectonic provinces of greater or less mobility. During periods of crustal compression or of crustal tension the stress conditions in provinces of different mobility might be notably different. During the post-Middle Miocene folding much of coastal California was strongly folded, while much of the

Canadian shield seems to have slept through the disturbance. No matter how closely vulcanism may be related to stress conditions, and no matter how nearly world-wide we assume crustal compressions or tensions to have been in the past, there would be no reason to expect the same volcanic phenomena in regions so different in mobility as these two. If analogies exist they could only be found by comparing the volcanic succession for a given period of time in tectonically similar regions.

It seemed at first that possibly something could be learned by finding out whether or not other great transgressions have been initiated to the accompaniment of widespread faulting and of outbreaks of basalts and rhyolites, but the evidence is unfortunately not very conclusive. Faults are notably hard to date. Those in the Santa Monica Mountains and San Joaquin Hills have been considered old because many of them are accompanied in part of their courses by dikes of basalt, considered to be Miocene in age. Geologists who objected to this view simply argued that these particular dikes are young, and this hypothesis for a long time seemed as satisfactory as the other. Volcanic rocks are also difficult to date, possibly because they are studied mostly by geologists who do not specialize in historical geology. It is surprising to see how many different dates are given in authoritative treatises and textbooks for such an important series of volcanic rocks as the Deccan lavas of India or the basalts of Scotland. The former are sometimes said to begin in the Cenomanian, for example, which would make them contemporaneous with the great Upper Cretaceous transgression; but they are said by others, with equal firmness, to be Paleocene, which would make them contemporaneous with the Laramide orogeny. Similarly the age of the Scottish lavas is either Eocene or Aquitanian, or something in between. So long as basaltic rocks are dated so loosely there is of course no chance to find out whether or not they have been erupted by preference at times of great transgressions.

Thus the problem cannot be solved here and now, but is nevertheless an important one for structural geology. If the relations that seem to hold in California are more than a coincidence, they would seem to favor such theories as those of Holmes and Joly, and to be opposed to others of similar scope that are based on different assumptions as to the state of the earth's interior and the causes of its movements. Since all such theories are based on mechanical concepts considered to be sound by those who hold them and unsound by those who oppose them, there is a distinct possibility that the efforts of a mere historical geologist, who might find out what has actually hap-

pened at different times and places in the world, would be of some relevance even for this fundamental problem of tectonics.

Another subject bearing on similar problems is that of the length of time required for orogenic disturbances. As already indicated, the Coast Range results suggest that the time may be very short, even as compared to the time represented by a faunal zone. This result is important if true, since it means that the existence of a considerable number of orogenic phases during the Tertiary is consistent with the hypothesis that orogeny is not a continuous process. It is also important for the reason that, the shorter an orogenic phase is supposed to be the more difficulty we shall have in demonstrating that the phases are actually world-wide. Perhaps we shall never be able to do so, for the reason that methods of correlation do not permit the very fine synchronizations that would be required for such a demonstration.

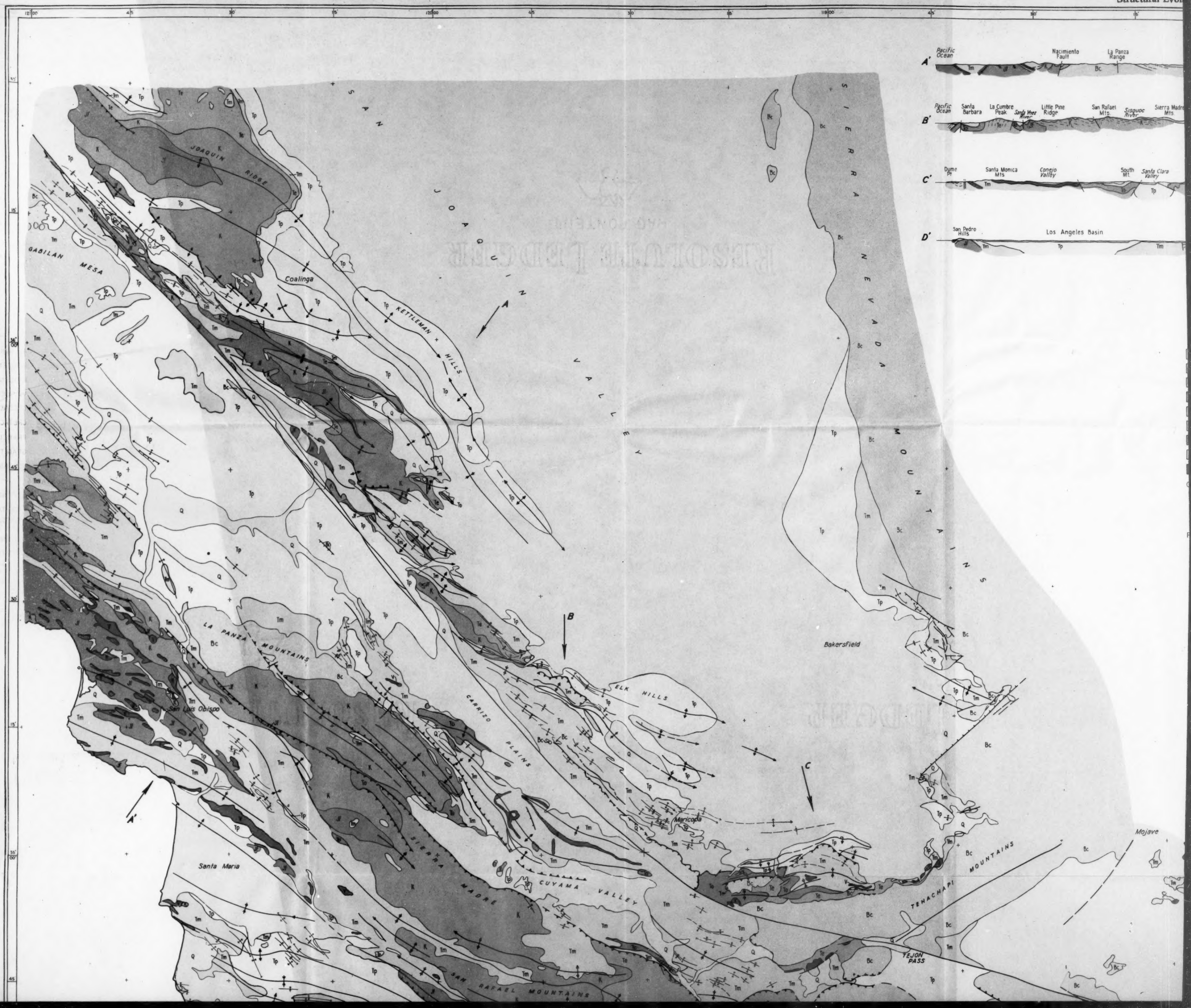
Some of the most interesting results of this study relate to the origin of thrust faults. Most of them, as explained already, seem to have originated under one or another of two sets of conditions. One set, including the Santa Ynez, Big Pine, and several other faults, developed along lines where a thick mass of sediments had been reduced by erosion to a thin edge. The cross-sections of the Santa Ynez district (Fig. 35) illustrate the conditions. The other set, including most of those that border the great Tertiary embayments—particularly their apical parts—seems to have come into existence where basin development had caused a strong epeirogenic flexure in the early Tertiary formations surrounding the basins. The conditions are illustrated strikingly in the cross-sections of the Ventura Basin (Fig. 39 and others). In some cases the two sets of conditions seem to occur together. That is, the fault is found at the margin of a basin, and also at the thin edge of a thick series of strata that thin toward the basin. Perhaps with sufficient ingenuity in philosophical reasoning the conditions necessary to account for the faulting could all be generalized and reduced to a single set, but for the present it seems best to discuss only appearances and to admit that thrust faults have originated under two different sets of conditions.

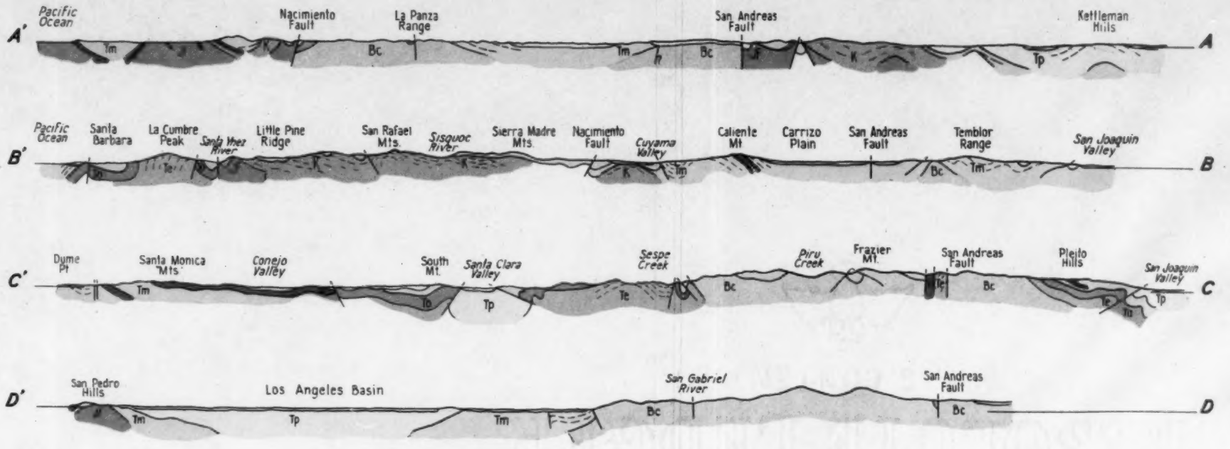
Although much has been written about the dominant direction of thrusting or of "release of pressure," the data now in hand serve to indicate pretty clearly that no direction is dominant for any great distance. An inspection of Plate I or of any of the local structure maps accompanying this volume will make this condition sufficiently evident.

Upon the problem of fault-troughs of deposition and upon the

nature of the faulting that may have produced such troughs if they exist, our results are unfortunately meagre. It seems safe to say, as has been said more than once before, that if fault-troughs exist they are probably limited to thin-blanketed, relatively stable areas, such as some of those in granitic provinces. The problem of the existence of such troughs is a difficult one to investigate by the historical method, because the age and history of faults are difficult to determine. Most of the large faults of California have been considered old by some geologists and young by others. Even if a fault is old but has been rejuvenated recently, the later movement tends to destroy the evidence for the earlier ones. In the case of the Whiterock fault at the southwest margin of the Caliente trough, the evidence available at present shows simply that the fault is post-Morales; that is, probably, post-Pliocene. In any case it is a thrust fault with the north side upthrown. If an earlier fault existed here and by its movements permitted the Caliente trough to subside, it was a normal fault with the north side downthrown. This is not to say that the existence of the later thrust fault disproves the existence of the earlier normal fault, but merely that the later fault known by observation should not be mistaken for the earlier fault needed as the physical foundation for a theory.

In conclusion, it may be worth mentioning again that this book represents primarily an effort to assemble some of the materials needed for theorizing about Coast Range structure. The theories presented herein are merely samples. Every reader, it may be, will be inspired to invent better theories for himself, and will readily succeed. If so, he should realize that in so doing he is helping fulfill the purpose for which the book was written.


SAN JOAQUIN VALLEY
SIERRA NEVADA MOUNTAINS
JOAQUIN RIDGE
GABILAN MESA
Coalinga
KETTLEMAN HILLS
LA PANZA MOUNTAINS
San Luis Obispo
CARRIZO PLAINS
ELK HILLS
Bakersfield
Maricopa
SIERRA MADRE
CUYAMA VALLEY
SAN RAFAEL MOUNTAINS
Santa Maria
TEHACHAPI MOUNTAINS
FEJON PASS
Mojave
A
A'
B
C
Pacific Ocean
Nacimiento Fault
La Panza Range
Santa Barbara
La Cumbre Peak
Santa Ynez River
Little Pine Ridge
San Rafael Mts.
Sisquoc River
Sierra Madre Mts.
Dume Pt.
Santa Monica Mts.
Conejo Valley
South Mt.
Santa Clara Valley
San Pedro Hills
Los Angeles Basin
Tm
Tp
Te
K
Jf
Bc
Q



LEGEND

- Q ALLUVIUM
- Tp PLIOCENE - PLEISTOCENE
- Tm MIOCENE
- To OLIGOCENE
- Te EOCENE
- K CRETACEOUS
- JF FRANCISCAN
- Bc GRANITE BASEMENT
- V VOLCANICS

CONTACTS

FAULTS
- MAJOR: NORMAL; THRUST; SHEAR OR UNKNOWN
- MINOR: NORMAL; THRUST; SHEAR OR UNKNOWN

AXES
- MAJOR: ANTICLINES; SYNCLINES
- MINOR: ANTICLINES; SYNCLINES

GENERALIZED TECTONIC MAP
OF
SOUTHERN CALIFORNIA

Scale

5 0 5 10 15 20 25

MILES

Compiled by R.D Reed and J.S. Hollister.

1936

Base of map compiled from U.S Geological Survey Topographic Maps
Geological data from all available published and unpublished sources.

SANTA BARBARA CHANNEL

SAN MIGUEL ISLAND

SANTA ROSA ISLAND

SANTA CRUZ ISLAND

ANACAPA ISLAND

SANTA CATALINA ISLAND

Santa Maria

Point Concepcion

Santa Barbara

Ventura

Dume Pt.

Mojave

Maricopa

SIERRA MADRE

CUYAMA VALLEY

SAN RAFAEL MOUNTAINS

SANTA YNEZ MOUNTAINS

TEHACHAPI MOUNTAINS

TEJON PASS

A'

B'

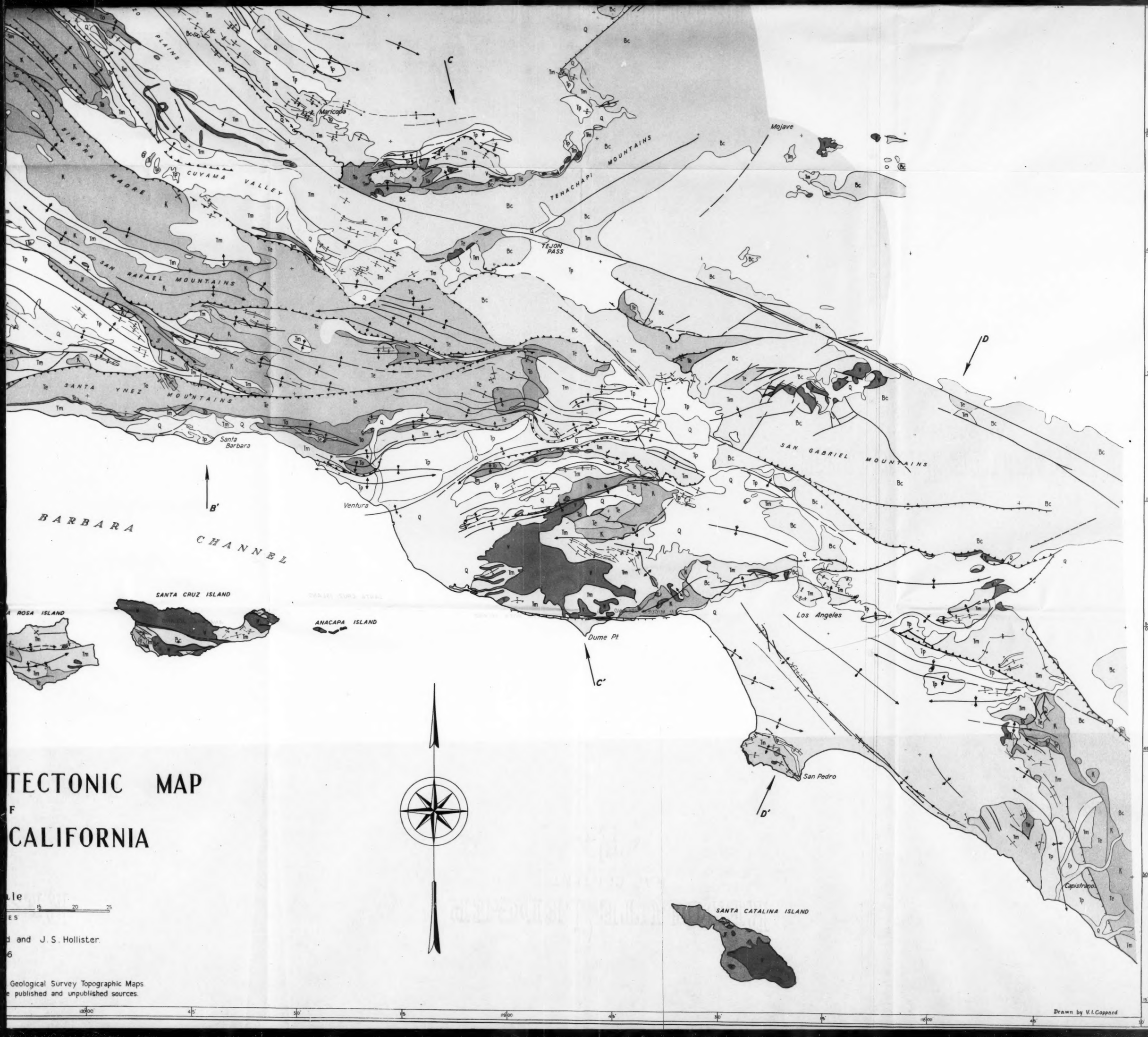
C'

C

D'

Q Quaternary
Tp Pliocene
Tm Miocene
Te Eocene
To Oligocene
K Cretaceous
Bc Basement complex

TECTONIC MAP
F
CALIFORNIA



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15 20 25

ES

d and J. S. Hollister.

6

Geological Survey Topographic Maps
e published and unpublished sources.

120°00' 45' 30' 15' 119°00' 45' 30' 15' 118°00' 45' 30'

Drawn by V. I. Coppard

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of the

AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

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of the
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THE AMERICAN ASSOCIATION OF
PETROLEUM GEOLOGISTS

PUBLISHED
MONTHLY

Composed and Printed by
George Banta Publishing Company
Menasha, Wisconsin, U.S.A.

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Page 450: last reference listed under MUIR, "Sobre el hallazgo . . . ," should be added to references under MÜLLERRIED on page 451.

Page 569, line 15: "*Rotalia beccarii* (Linne)" should be "*Discorbis* cf. *D. vilardeboana*."

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MONTHLY

Composed and Printed by
George Banta Publishing Company
Menasha, Wisconsin, U.S.A.

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ERRATA

Page 1273, last line: "CARY P. BUTCHER" should be J. H. MCCLURE.

BULLETIN

of the

AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

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THE SUBSCRIPTION PRICE to non-members of the Association is $15.00 per year (separate numbers $1.50) prepaid to addresses in the United States. For addresses outside the United States, an additional charge of $0.40 is made on each subscription to cover extra wrapping and handling.

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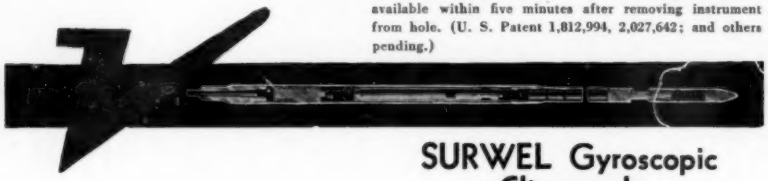

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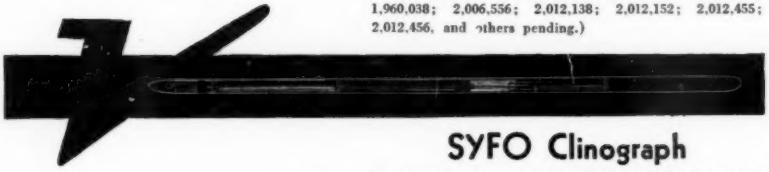

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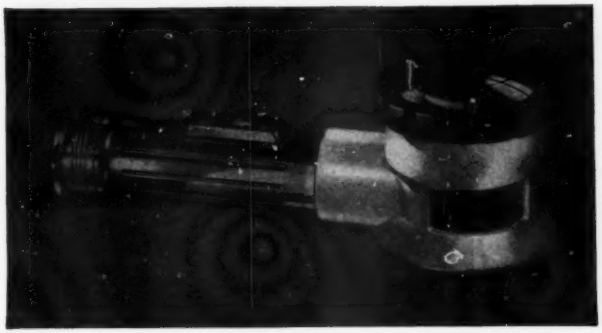

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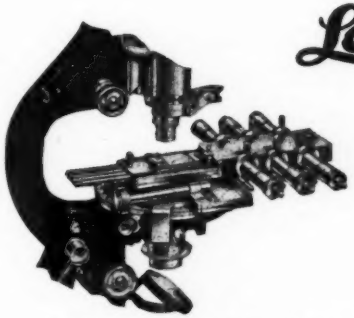

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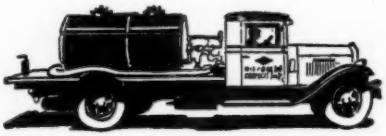

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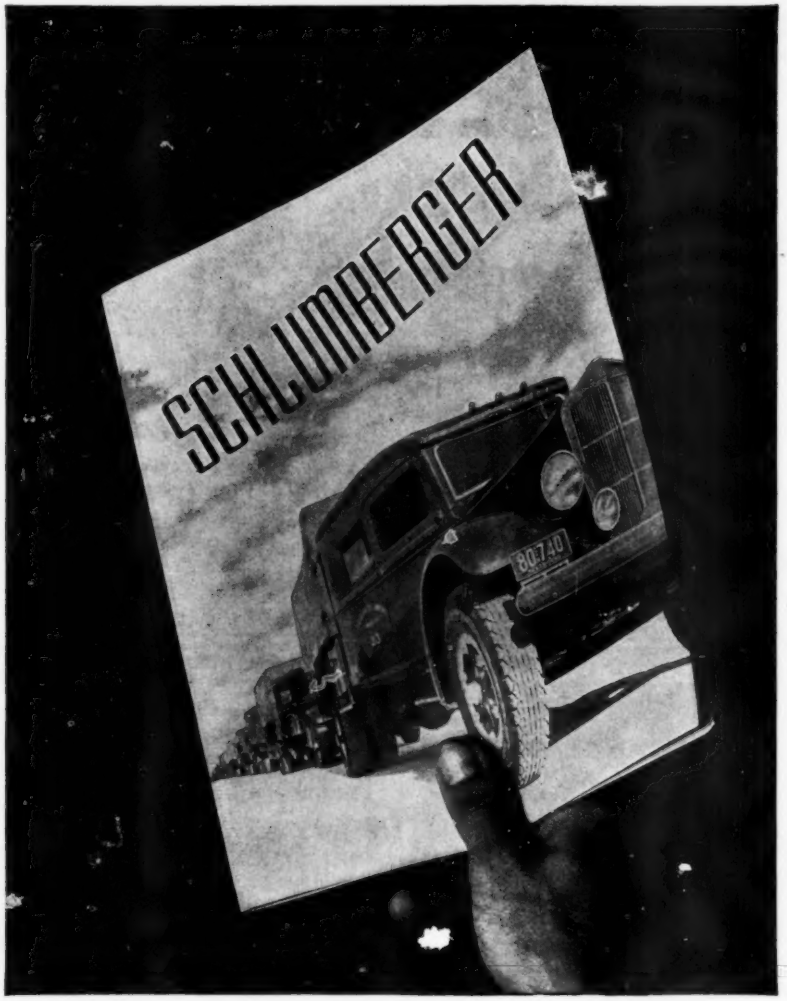

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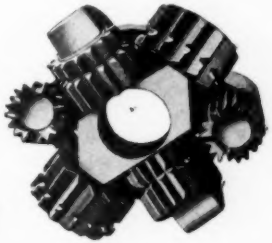

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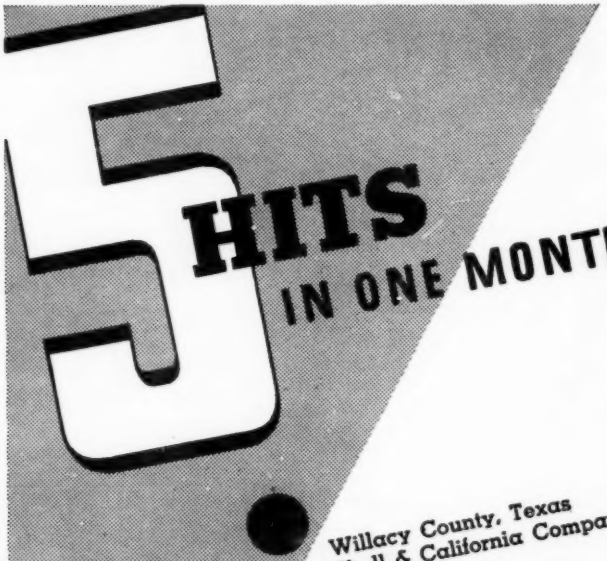

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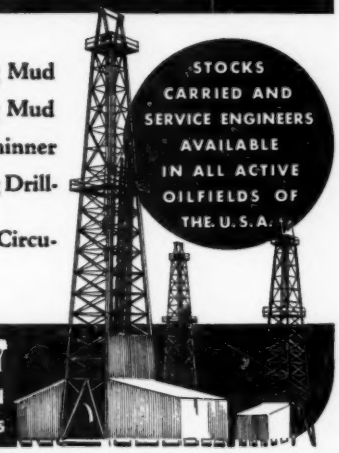

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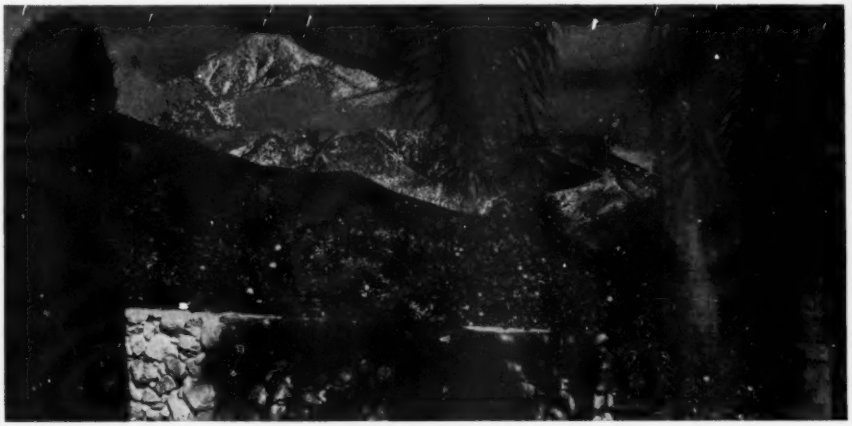

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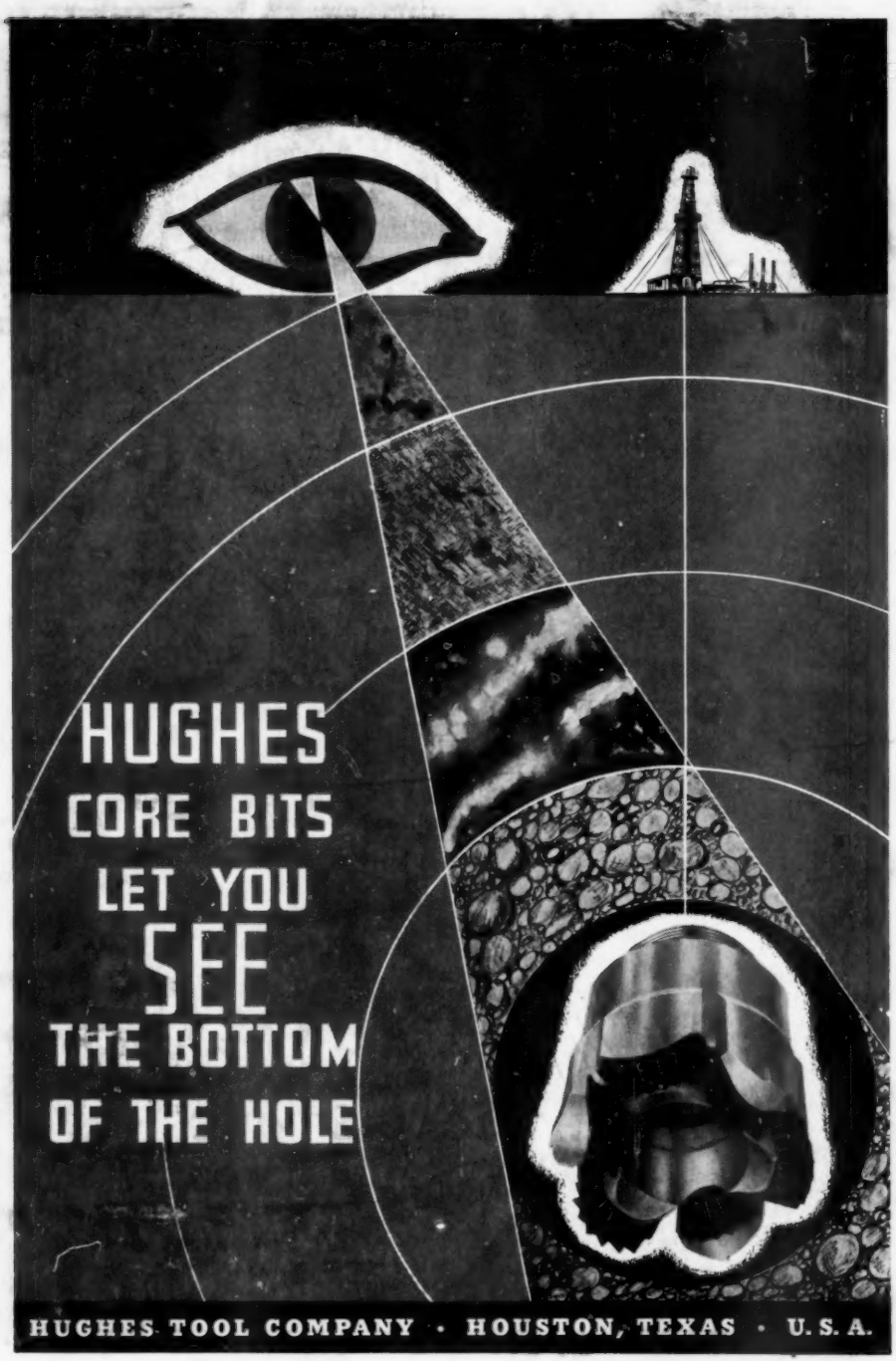
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